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APiP-2019

20th International Conference on Atomic Processes in Plasmas

April 9-12, 2019

National Institute of Standards and Technology

Gaithersburg, MD, USA

https://pml.nist.gov/apip2019

Welcome to the 20th International Conference on Atomic Processes in Plasmas!

APiP 2019 will be held on the campus of the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland.

The APiP meetings started in 1977 as the American Physical Society (APS) Topical Conferences. However, since 2007 the APiP conferences have become International, to better reflect the true nature of the meeting. More information on the history of the APiP conference series is available from the NIST Physical Measurement Laboratory pages at https://physics.nist.gov/Meetings/APIP/history.html.

The APiP conference focuses on atomic processes that are involved in the study of various plasmas over a wide range of densities and temperatures (eV to a few keVs).

The topics will include, in particular:

- Astrophysical plasmas
- Fundamental Data and Modeling
- High Energy Density Plasmas
- Low Temperature and Industrial Plasmas
- Magnetic-Fusion Plasmas
- Measurements of Atomic Processes
- Powerful Light Sources (XFEL, etc.)
- Small-scale Plasmas (table-top lasers, EBITs, etc.)
- Warm Dense Matter

The APiP 2019 scientific program consists of invited talks, oral contributions, and posters.

We thank you for joining us at NIST and sincerely hope that you will enjoy the conference!

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Campus Map


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Conference Program

Tuesday April 9		
8:50-9:00	**Opening**	
<u>High energy density physics</u>		
9:00-9:35	**M.B. Schneider** (LLNL, USA)	*X-ray spectroscopy and atomic physics of relevance to inertial confinement fusion*
9:35-10:10	**Z. Harman** (MPIK, Heidelberg, Germany)	*Narrow-band hard-x-ray lasing with highly charged ions*
10:10-10:30	**K. Hill** (PPPL, USA)	*Inference of electron density in the hot spot of NIF capsules from krypton helium-β Stark line shapes*
10:30-11:00	**Coffee break**	
<u>Atomic data for plasmas</u>		
11:00-11:35	**N. Nakamura** (Univ. of Electro-Communications, Tokyo, Japan)	*Measurement of high-multipole forbidden transitions in highly-charged ions produced with EBITs*
11:35-12:10	**G. Nave** (NIST, USA)	*Atomic data to trace the chemical history of the galaxy*
12:10-12:30	**J. Scheers** (ARCNL, The Netherlands)	*EUV spectroscopy on highly-charged tin ions in an electron beam ion trap*
12:30-13:30	**Lunch**	
<u>Astrophysical plasmas</u>		
13:30-14:05	**N.S. Brickhouse** (CfA-Harvard Univ., USA)	*Recent advances in x-ray spectroscopy of astrophysical plasmas*
14:05-14:40	**G. Loisel** (SNL, USA)	*A benchmark experiment for x-ray emission and temperature*

		diagnostics in accretion-powered photoionized plasmas
14:40-15:00	**A. Gall** (Clemson Univ., USA)	*Analysis of the contribution of Ar dielectronic recombination lines to the unknown faint x-ray feature found in the stacked spectrum of galaxy clusters*
15:00-15:30	**Coffee break**	
Magnetic fusion plasmas		
15:30-16:05	**B. Lomanowski** (ORNL, USA)	*Interpretation of opacity measurements in the JET ITER-like wall divertor using a particle balance approach*
16:05:16:40	**A.E. Järvinen** (LLNL, USA)	*Use of VUV spectroscopy in validation of DIII-D boundary science during radiative divertor operation*
16:40-17:00	**E. Flom** (Univ. of Wisconsin—Madison, USA)	*The He/Ne beam diagnostic for line ratio spectroscopy in the Island Divertor of Wendelstein 7-X*

Wednesday April 10		
Warm dense matter		
9:00-9:35	**T. Nagayama** (SNL, USA)	*Systematic measurements of opacity dependence on temperature, density, and atomic number at stellar interior conditions*
9:35-10:10	**G.O. Williams** (Univ. de Lisboa, Portugal)	*Impact of free-electron quantum effects on collisional rates in plasmas*
10:10-10:30	**I.E Golovkin** (Prism Comp. Sci., USA)	*New Prism EOS and Opacity Tables with NLTE Atomic Kinetics*
10:30-11:00	**Coffee break**	
Low-temperature plasmas		
11:00-11:35	**O. Marchuk** (Forschungszentrum Jülich, Germany)	*Emission of fast hydrogen atoms in a low density gas discharge: the most "natural" mirror laboratory*
11:35-12:10	**E.H. Martin** (ORNL, USA)	*Electric and magnetic field measurements using Doppler-free saturation spectroscopy*
12:10-12:30	**V. Kokoouline** (Univ. of Central Florida, USA)	*"Universal" theoretical approach for determination of cross sections for dissociative recombination, rotational, vibrational, electronic excitation of molecular ions*
12:30-13:30	**Lunch**	
High energy density plasmas		
13:30-14:05	**C.G. Parigger** (Univ. of Tennessee, USA)	*Atomic and molecular spectroscopy and self-absorption measurements*

14:05-14:40	**A. Dasgupta** (NRL, USA)	*Spectroscopic diagnostics using line-radiation in laser driven non-equilibrium plasmas*
14:40-15:00	**J. Sheil** (Univ. College Dublin, Ireland)	*Spectroscopy of laser-produced lanthanum plasmas in the 0.8 – 4.2 nm region*
15:00-17:00	**Coffee break and <u>POSTERS</u>**	

Thursday April 11		
<u>Magnetic fusion plasmas</u>		
9:00-9:35	**T. Pütterich** (MPIP, Germany)	*Impurities in a magnetically confined fusion reactor*
9:35-10:10	**C. Suzuki** (NIFS, Japan)	*Soft x-ray spectroscopy of rare-earth elements in LHD plasmas*
10:10-10:30	**C. Hill** (IAEA, Austria)	*Recent activities in atomic and molecular data at the IAEA*
10:30-11:00	**Coffee break**	
<u>X-ray sources</u>		
11:00-11:35	**H.J. Lee** (SLAC, USA)	*Observation of Fe Kα emission spectra under keV temperature solid-density conditions*
11:35-12:10	**F. Dorchies** (Univ. de Bordeaux, France)	*Comparison of x-ray sources generated from sub-ps laser-plasma interaction on clusters and solid targets*
12:10-12:30	**M.J. May** (LLNL, USA)	*Development of high fluence x-ray sources using laser heated novel nano-wire metal foams*
12:30-13:30	**Lunch**	
<u>Low-temperature plasmas</u>		
13:30-14:05	**T.C. Killian** (Rice Univ., USA)	*Laser cooled neutral plasmas: a laboratory for the study of strongly coupled systems*
14:05-14:40	**I.F. Schneider** (Univ. du Havre, France)	*Electron-molecular cation collisions in cold plasmas*
14:40-15:00	**M.C. Zammit** (LANL, USA)	*Molecular data for hydrogen plasma modeling*

15:00-15:30	**Coffee break**	
<u>Astrophysical plasmas</u>		
15:30-16:05	**D.R. Schultz** (North Arizona Univ., USA)	*Atomic processes at Jupiter: ion and secondary-electron transport from swift ion precipitation into the Jovian upper atmosphere*
16:05:16:40	**C.J. Fontes** (LANL, USA)	*A link between atomic physics and gravitational wave spectroscopy*
16:40-17:00	**Dipti** (NIST, USA)	*Polarization of K-shell x-ray transitions in highly charged ions of Ar*

19:30-…	**Dinner (Guapos, Washingtonian Rio)**	

Friday April 12		
9:00-9:35	**R. Piron** (CEA, France)	*Atomic processes in dense plasmas through the average-atom approach*
9:35-10:10	**T.A. Gomez** (SNL, USA)	*An effort to reconcile electron-broadening theories*
10:10-10:45	**S. Ferri** (Aix-Marseille Univ., France)	*Stark-Zeeman line shapes model for multi-electron radiators in hot and dense plasmas submitted to large magnetic fields*
10:45-11:05	**Coffee break**	
High energy density plasmas		
11:05-11:40	**F.P. Condamine** (ELI Beamlines, Czech Republic)	*Observation of first resonance pumping of x-ray line profiles of highly charged ions in dense plasmas at LCLS-MEC*
11:40-12:15	**D.C. Mayes** (Univ. of Nevada Reno, USA)	*Investigating atomic kinetics in photoionized plasma experiments using x-ray transmission spectroscopy*
12:15-12:35	**R. Schupp** (ARCNL, The Netherlands)	*Scaling of emission efficiency and optical depth in dense 1μm-laser-driven Sn plasmas*
12:35-12:40	**Meeting adjourns**	

Posters

#1	**A. Kramida** (NIST, USA)	*NIST Atomic Databases and Online Tools for Plasma Physics*
#2	**J. Deprince** (Univ. de Mons, Belgium)	*Atomic Data for Modeling the Fe K-Lines in High-Density Astrophysical Plasma Environments: Radiative, Auger and Photoionization Processes*
#3	**J. Rosato** (Aix-Marseille Univ., France)	*Quantifying the Statistical Noise in Computer Simulations of Stark Broadening*
#4	**J. Ward** (UMD, USA)	*Spectrum of Ni V in the Vacuum Ultraviolet*
#5	**B. F. Kraus** (Princeton Univ., USA)	*Plasma Conditions in Short-Pulse-Heated Buried Tracer Layers from Fine-Structure X-ray Emission*
#6	**Hala** (NIST, USA)	*Wavelengths, Energy Levels, Hyperfine Structure and Oscillator Strength Measurement of Sc I and Sc II*
#7	**O. Peyrusse** (Aix-Marseille Univ., France)	*Prospects concerning 1D photonic crystals in the X-ray range*
#8	**J.E. Rice** (PSFC MIT, USA)	*X-ray Observations of Ne-like Xe from C-Mod Tokamak Plasmas*
#9	**Q. Min** (Northwest Normal Univ., China)	*Investigation of radiation and dynamics properties in laser-produced plasma*
#10		

#11	**H.A. Scott** (LLNL, USA)	*Free-Electron Degeneracy Effects for Collisional-Radiative Codes*
#12	**A.S Naing** (NIST, USA)	*A Miniature Dual-anode Electron Beam Ion Trap to Generate Highly Charged Ions with Low Ionization Threshold*
#13	**J.N. Tan** (NIST, USA)	*Capture of highly charged ions in a hyperbolic Paul trap*
#14	**L. Gao** (PPPL, USA)	*Time-Resolved Measurements of the Hot Spot Density and Temperature on the National Ignition Facility*
#15	**S.C. Sanders** (Clemson Univ., USA)	*D-line doublet observations of Na-like ions*
#16	**C. Mendoza** (Western Michigan Univ., USA)	*Effects of Dielectronic Recombination in Astrophysical Plasmas: Reflection Spectrum of a Black-Hole Accretion Disk*
#17	**C. H. Yuen** (Univ. of Central Florida, USA)	*Simplified model to treat the dissociative electron attachment of complex molecules*
#18	**Q. Lu** (Fudan Univ., China)	*Observation of Indirect Ionization of* W^{7+} *in EBIT plasma*
#19	**S. Gupta** (IIT, India)	*Collisional Radiative Model for Zn laser produced plasma*

Invited Talks

X-ray Spectroscopy and Atomic Physics of Relevance to Inertial Confinement Fusion

M. B. Schneider[1], E. V. Marley[1], J. Emig[1], M. E. Foord[1], Y. R. Frank[1], R. F. Heeter[1], L. C. Jarrott[1], G. E. Kemp[1], D. A. Liedahl[1], C. W. Mauche[1], G. Perez-Callejo[2], K. Widmann[1], M. Bitter[3], P. Efthimion[3], L. Gao[3], K. W. Hill[3], R. Kauffman[1], B. F. Kraus[3], M. J. Macdonald[1], A. G. MacPhee[1], Y. Maron[4], H. A. Scott[1], and D. B. Thorn[1]

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In inertial confinement fusion [1], laser energy is converted into an x-radiation drive in a high-Z cavity (“hohlraum”). The resulting thermal (~300 eV) x-rays heat a thin spherical shell of low Z material which ablates and, through a rocket-effect, drives the DT fuel inside to high enough temperature and density for fusion to occur. Many physical processes are involved in this integrated experiment, and benchmarking models for these physical processes or measuring plasma conditions is important for understanding and interpreting results. We use x-ray spectroscopy to better understand both hohlraum physics and capsule physics. We study the non-Local Thermodynamic Equilibrium (NLTE) physics [2] of the laser deposition region with surrogate experiments (on uniform plasmas) at the OMEGA laser [3]. We study conditions inside the capsule with high-resolution time-resolved x-ray spectroscopy [4] plus time-integrated continuum measurements [5] of Kr-doped fuel [6]. Current experimental results and comparison to atomic physics models will be presented.

References

[1] J. Lindl et al., Phys. Plasmas **21** 020501 (2014)
[2] H. A. Scott and S. B. Hansen **6** 39 (2010)
[3] E. V. Marley et al., Rev. Sci. Instrum. **89** 10F106 (2018)
[4] H. Chen et al., Phys. Plasmas **24** 072715 (2017)
[5] L. Gao et al., Rev. Sci. Instrum. **89** 10F125 (2018)
[6] D. B. Thorn et al., SPIE Proceedings **10390** 1039009 **(2017)**

* *This work was performed under the auspices of the U.S. Department of Energy by LLNS, LLC, under Contract No. DE-AC52- 07NA27344.*

Narrow-band hard-x-ray lasing with highly charged ions

Z. Harman, C. Lyu, S. M. Cavaletto, and C. H. Keitel

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The development of high-quality x-ray sources with well-defined intensity and frequency is of great importance in several areas of science. We present a scheme for the generation of fully coherent x-ray radiation via population inversion in highly charged ions [1]. The ions are generated in a laser-produced plasma and population inversion is achieved by inner-shell photoionization using x-ray pulses from a free-electron laser (FEL). In such systems, the autoionization channel hindering the lasing process is nonexistent due to the lack of outer-shell electrons. By choosing a lasing transition which decays slowly, on the one hand, it enables lasing for photon energies above 10 keV, on the other hand, it results in a further reduction of the x-ray laser bandwidth by several orders of magnitude, as compared to existing methods using neutral atoms or ions in low charge states as lasing medium [2,3].

For a time-dependent description of the process we solve the Maxwell–Bloch equations numerically with different realizations of simulated FEL pulses originating from self-amplified spontaneous emission. Atomic structural properties are obtained with the multiconfiguration Dirac-Fock method. Initial populations of the states of the involved highly charged ions under given plasma conditions are computed with the FLYCHK code [4]. Our theoretical simulations show that with the scheme we put forward one may obtain high-intensity, femtosecond x-ray pulses of relative bandwidths on the order of $\Delta\omega/\omega = 10^{-5}$–$10^{-7}$, and with photon energies up to the hard x-ray regime. Such x-ray lasers may be applicable, e.g., in the study of x-ray quantum optics and metrology, investigating nonlinear interactions between x-rays and matter, or in high-precision spectroscopy studies in laboratory astrophysics.

References

[1] C. Lyu, S. M. Cavaletto, C. H. Keitel, Z. Harman, "Narrow-band hard-x-ray lasing", submitted; arXiv:1801:02503.
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Measurement of High-Multipole Forbidden Transitions in Highly-Charged Ions Produced with EBITs

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Studies of high-multipole forbidden transitions in highly charged ions are important not only for testing atomic physics theory describing the interaction with high-multipole radiation fields, but also for several applications, such as plasma diagnostics [1] and atomic clocks [2]. An electron beam ion trap (EBIT) is a powerful device for studying such high-multipole transitions of highly charged ions. In an EBIT, highly charged ions are trapped for many hours while being excited by a relatively low-density (typically 10^{10}-10^{12} cm^{-3}) electron beam. The collision frequency is typically in the order of 10 Hz, so that forbidden transitions with a transition probability down to the order of 10 s^{-1} can be observed with an intensity comparable with that of electric dipole (E1) allowed transitions.

In this talk, we present our recent observations mainly performed with a compact electron beam ion trap, called CoBIT [3]. In particular, we have successfully observed electric octupole (E3) transitions in Ag-like W [4]. On the other hand, we have found that the existence of a strongly forbidden E3 transition in the Pm-like isoelectronic system can result in nearly complete population trapping at the $4f^{13}5s^2$ metastable state even though the ground-state configuration is alkali-metal-like $4f^{14}5s$ [5]. Population kinetics for these systems is discussed through the comparison with the analysis based on a collisional radiative model.

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Atomic Data to Trace the Chemical History of the Galaxy

G. Nave
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The first stars formed in the Universe were massive and short-lived, creating the heavier elements we know today and contributing them to the Galaxy in supernovae. Their influence can be studied through the elemental abundances of metal-poor stars found in the Galactic halo. The abundance patterns in these stars are quite different to the Sun and mounting evidence suggests that the lighter iron-group elements, Sc, Ti and V, were formed in a different way to the other iron-group elements in these stars [1]. This evidence relies on high quality laboratory wavelengths, oscillator strengths and hyperfine structure constants for many lines in both neutral and singly-ionized elements. The analysis of large numbers of spectral lines in metal-poor stars reduces the sensitivity of the analysis to the model atmosphere and indicates possible deviations from local thermodynamic equilibrium. Since the spectra of metal-poor stars are quite different to the spectrum of the Sun, different sets of lines are required for abundance measurements, and accurate atomic data are thus crucial.

Groups at the National Institute of Standards and Technology (NIST), Imperial College London (ICL), and the University of Wisconsin-Madison (UW) have been active in the measurement of these atomic data for many decades. Wavelengths, energy levels, and hyperfine structure constants are measured using high-resolution Fourier transform (FT) and grating spectrometers at NIST and ICL. Oscillator strengths combine a measurement of atomic lifetimes at UW with branching fractions measured using NIST and ICL FT spectrometers, with weaker branches measured using a high-resolution echelle spectrometer at UW. The uncertainties in these oscillator strength measurements are now dominated by the branching fractions rather than the lifetimes. This is particularly the case when lines used for abundance measurements are widely separated in wavelength from the dominant lines from the upper level of the transition and require more than one standard lamp for radiometric calibration.

I shall present our current work on measurements of atomic data for neutral and singly-ionized iron-group elements. I shall illustrate some of the problems in measuring branching fractions using a recent study of Sc II [2], where the correction of previous oscillator strengths of the visible lines most widely used for abundance determinations has resulted in an increase in the transition probabilities of over 20% for some lines, several times the estimated uncertainty.

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[1] C. Sneden, J. J. Cowan, C. Kobayashi, M. Pignatari, J. E. Lawler, E. A. Den Hartog, M. P. Wood, Astrophys. J. **817**, 53 2016.
[2] J. E. Lawler, Hala, C. Sneden, G. Nave, M. P. Wood, J. J. Cowan, Astrophys. J. Suppl. Ser. (in press).

Recent Advances in X-ray Spectroscopy of Astrophysical Plasmas

N. S. Brickhouse

Center for Astrophysics | Harvard Univ. & Smithsonian

High resolution X-ray spectra provide insight into some of the most extreme physical conditions and energetic processes in the Universe. New results include: the discovery of some of the "missing" baryons in the warm hot intergalactic medium [1]; the inference of collisionless electron heating of the reverse shock in a young supernova remnant [2]; and the accretion-driven physics in a young stellar corona.[3] While these results are exciting, astronomical X-ray spectroscopy is still limited to a few bright sources, with modest spectral resolution and signal-to-noise. Proposed missions in the future will provide new diagnostics for understanding astrophysical plasmas. We will not only find more baryons but complete the metal census of the Universe using soft X-ray absorption lines; use reverberation mapping to localize the source of winds in AGN; and test solar coronal heating models on stars using dielectronic recombination satellites. New capabilities will expand high resolution spectroscopy to extended sources and crowded fields, while also providing velocity resolution down to ~10 km/sec.

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A benchmark experiment for x-ray emission and temperature diagnostics in accretion-powered photoionized plasmas

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A highly reproducible platform was developed on the Z facility for the study of photoionized plasmas in the ~20-200 erg.cm/s photoionization regime. Absorption and emission spectra were measured down to 5% reproducibility with high spectral resolution making the data suitable to benchmark photoionization and line formation models. These experiments have measured, for the first time in the laboratory, the radiative recombination continuum (RRC) from photoionized plasma that is used to determine the temperature of accretion-powered plasmas around compact objects. On Z, a careful experiment design was necessary to overcome the harsh environment associated with the MJ-class x-ray source, such that faint RRC emission from H-like to He-like silicon along with the He-like *n*p-1s, $n \leq 14$, series could be observed. Simultaneously, the temperature is inferred from the absorption spectrum under the partial LTE assumption providing a unique test on the temperature diagnostic accuracy.

Sandia National Laboratories is a multimission laboratory managed and operated by NTESS LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. DOE's NNSA under contract DE-NA0003525.

Interpretation of opacity measurements in the JET ITER-like wall divertor using a particle balance approach

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Recent improvements in spectroscopic measurements of the JET ITER-like wall divertor plasma temperature and density have facilitated estimates of the outer target volumetric ion source and sink rates using ADAS [1] inverse photon efficiency coefficients. In high-recycling outer divertor conditions a factor of three shortfall was found in the ionization rate obtained from Ly_α intensity profiles compared to the reference D_α estimates. Additionally, radial profiles of the $(Ly_\beta/D_\alpha)(A_{D\alpha}/A_{Ly\beta})$ ratio suggest strong opacity of the Ly series lines at the outer target. To reconcile the Ly_α ionization rate discrepancy, a detailed interpretation of opacity corrections using the population escape factor approach [2] is presented. To aid in the measurement interpretation and assessment of the impact of spectroscopy line-integration effects, an *ad hoc* opacity model is employed using the EDGE2D-EIRENE [3] fluid-neutral code package. Post-processing of the simulations with synthetic spectroscopy shows good correspondence to experiment which reinforces the estimated Ly_β and Ly_α escape factor values at the outer target of less than 0.5 and 0.1, respectively, (i.e., more than 50% Ly_β and 90% Ly_α photon reabsorption along the vertical line-of-sight). These findings suggest a renewed effort should be undertaken in the assessment of the opacity impact on both diagnostic interpretation and divertor plasma dynamics using the more sophisticated EIRENE photon transport model [4] in the context of metal wall tokamaks.

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**See the author list of "Overview of the JET results in support to ITER" by X. Litaudon et al. 2017 Nucl. Fusion 57 102001.*

Use of VUV Spectroscopy in Validation of DIII-D Boundary Science During Radiative Divertor Operation*

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A VUV spectrometer viewing the peak plasma radiation near the vessel wall components (Divertor SPRED) was installed in the DIII-D tokamak to resolve discrepancies between measured and predicted radiated power. Next step, reactor-scale magnetic confinement fusion devices are expected to exhaust most of their plasma heat radiatively rather than conductively to avoid exceeding the engineering limits of the vessel wall components [1]. In these radiative divertor conditions, the plasma flowing along the field lines towards solid surfaces is cooled from electron temperatures above $T_e \sim 70$ eV down to sub eV, and the electron density is increased from a few $n_e \sim 10^{19}$ m^{-3} to about $10^{20} – 10^{21}$ m^{-3}. A rich phenomenology of multiple atomic and molecular physics processes from excitation to recombination with strong impurity radiation convert the plasma heat to radiated power. However, 2D fluid codes, used for predicting these conditions in the next step devices, do not generally predict radiation accurately for existing devices [2, 3]. The newly installed divertor SPRED is capable of measuring directly the intensity of the dominant resonant radiating lines, such as Ly-α (1215 Å), CIV (1550 Å), and NV (1238 Å). The spectrometer also covers the spectral region of molecular Lyman-Werner bands. Together with the bolometer measuring the total radiated power and the divertor Thomson scattering system measuring n_e and T_e, these measurements provide direct constraints for most of the key ingredients of radiated power calculations in these models.

Similar to previous studies with divertor SPRED in DIII-D, in strongly radiative conditions induced by deuterium injection, the resonant CIV (1550 Å) line dominates radiated power near the X-point in the divertor, while Ly-α radiation dominates near the target [4]. In plasmas with strong nitrogen injection, NV (1238 Å) provides the strongest contribution to radiated power near the X-point. While 2D simulations capture qualitatively many of the radiative features seen in the experiment, there are still significant quantitative discrepancies, which will be elaborated.

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Work supported by the US DOE under DE-FC02-04ER54698 and DE-AC52-07NA27344, and LLNL LDRD project 17-ERD-020.

Impact of free-electron quantum effects on collisional rates in plasmas

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A plethora of scientifically and practically relevant plasma environments exist at a temperature and density in which quantum mechanics shapes the behavior of the free electrons. In these conditions, quantum effects can influence any bound electron transitions to or from the free-electron continuum. However, a full quantum mechanical treatment of the bound and free electrons is computationally impossible. Instead, we parameterize the quantum effects and include them in existing collisional radiative models, allowing a tractable way to model ionization dynamics in these exotic plasmas. We present the theoretical framework and supporting experimental evidence for these effects.

The use of x-ray free electron lasers to create and characterize solid density plasmas has opened a new window to the microphysics of extreme states of matter. W use this method to explore the impact of free-electron degeneracy on the collisional rates in solid density plasmas. We observe experimentally ion satellites of the k-alpha transition in warm dense aluminum with a magnitude far above those predicted with standard collisional-radiative treatments. We attribute the prominence of the ion satellites to a reduction in collisional recombination within the L-shell, due to the degeneracy of the free electrons. This effect can be included in existing codes in the form of correction factors to the various transition rates. We show that by including a correction factor in the collisional-radiative code FLYCHK, a much-improved fit to the experimental data is found.

Emission of fast hydrogen atoms in a low density gas discharge: the most “natural” mirror laboratory

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The emission of hydrogen atoms at plasma solid interface is one of the most studied fields covering the topics of laboratory, astrophysical or fusion plasmas. In this work we demonstrate a new application for the line shapes of emission induced by reflected atoms: *optical properties* of the solids in contact with the plasma could be effectively measured at the wavelength of Balmer lines. The time-resolved measurement of the spectral reflectance of mirror surfaces in the optical laboratories is replaced using the wavelength separation of the direct and reflected signals *in situ* during plasma operation. One uses the Doppler effect of emission of H atoms excited by collisions with noble gases, primarily with Ar or with Kr in the energy range of 100-300 eV to separate the signals. The crucial condition for such measurements is the absence of emission induced by fast atoms in the Child-Langmuir sheath. The operational limits differ from Grimm type discharges considerably. The so-called DSRM (**D**oppler-**S**hifted **R**eflectance **M**easurements) diagnostics can be used to obtain the values of spectral reflectance, degree of polarization by reflection but also for *in-situ* monitoring the degradation of optical properties in the absence of other light sources [1, 2]. The measurements were performed in a weakly magnetized (gas pressure of 0.1 Pa, magnetic field of 0.1 T, electron density 10^{11} cm^{-3} and electron temperature of 3-5 eV) linear plasma facility PSI-2. The very good agreement between the results of the DSRM diagnostic and measurements in the laboratory is obtained for many materials including Al, Ag, C, Cu, Rh, Fe, Mo and W. The data for the energy (above 50 eV) and angular distribution of reflected atoms are obtained as results of the modelling of emission.

Nonetheless, in spite of unexplored application of the DSRM diagnostic, the crucial question on the source of the strong signal in case of Ar exists still. The emission signal observed in case of excitation of H or D atoms by Ar exceeds the signal induced by collisions with Kr atoms by a factor of five [3]. The only available experimental data for the ground state excitation shows practically equal cross-sections for both gases in the energy range of study [3]. The excitation by collisions with ions can be excluded on the basis of experimental data. Instead, another possible source of excitation of hydrogen atoms remains the metastable fraction of Ar. The latter was measured independently using the laser absorption spectroscopy at PSI-2. The new data of metastable fraction demonstrate a relatively flat profile so that the excitation transfer could be not excluded completely. Finally, the work summarizes *pros- and cons-* arguments for excitation of hydrogen atoms by the ground state or the metastable fraction of Ar.

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Electric and Magnetic Field Measurements using Doppler-Free Saturation Spectroscopy

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Electric (**E**) and magnetic (**B**) field vectors are fundamental variables in the equations governing plasma physics – specifically – the Boltzmann and Maxwell equations. For this reason, a direct measurement of these vectors can provide a powerful diagnostic for the investigation of plasma and fusion science. In this presentation, an overview of a laser-based technique capable of locally measuring electric and magnetic field vectors will be discussed. The spectroscopic setup and quantum mechanical modeling required to obtain Gauss and V/cm scale resolution will be presented. Finally, the technique's capability will be demonstrated by presenting experimentally measured He I 2^1P to 5^1D spectra experiencing a magnetic field ranging from 600 to 900 Gauss.
Spectroscopy is a common technique used to measure magnetic and electric field vectors through the splitting of the spectral line profile. These phenomena are known as the Zeeman and Stark effect, respectively. Passive measurements based on observing spontaneous emission from excited states have been quite successful for large amplitude fields ($|\mathbf{B}|$>5000 Gauss and $|\mathbf{E}|$>1000 V/cm). However, to measure small amplitude fields active methods must be employed to reduce and/or eliminate spectral broadening mechanisms. The measurement of small amplitude fields is of significant importance for the heating, equilibrium, and stability of plasmas. Doppler-free saturation spectroscopy (DFSS) is an active laser-based technique capable of such measurements. This is possible because DFSS measured spectra can have a resolution that approaches the Heisenberg uncertainty principle, yielding access to the complete quantum structure of the electron.
DFSS is based on exciting electronic transitions using a tunable laser source. The spectrum is obtained by measuring the absorbed laser power as the laser frequency is swept over the transitions of interest. To obtain the Doppler-free resolution, the laser beam is split (90/10) into two separate beams referred to as the pump and probe. The beams are aligned such that they are counterpropagating at a small angle and overlap over at the desired measurement location. The counterpropagating geometry allows the detection of excitation events that occur in atoms having a velocity vector perpendicular to both beams. The result is an effective reduction in the Doppler broadening. In general, precise quantum mechanical and atomic physics modeling is required to extract the electric and/or magnetic field vector from DFSS measured spectra with Gauss and V/cm resolution. This stipulation is due to the complex behavior of the quantum states, optical pumping, and the crossover resonance.
DFSS has been successfully implemented in the Laser Spectroscopy and Quantum Sensing Laboratory (LsQsL) at ORNL to measure helium and hydrogen spectra with a x1000 reduction in the Doppler broadening. These measurements were conducted in a magnetized plasma source capable of operating in the range of $|\mathbf{B}|$=600 to 900 Gauss. In this presentation, DFSS measured π and σ polarized He I 2^1P to 5^1D spectra experiencing Zeeman splitting due to a magnetic field ranging from 600 to 900 Gauss will be presented. The results obtained from fitting the spectra to the Schrodinger equation accounting for optical pumping and crossover resonance effects will be discussed, highlighting the impressive capability of laser-based spectroscopy.

Atomic and Molecular Spectroscopy and Self-Absorption Measurements

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This work discusses laboratory measurements of atomic and diatomic molecular species in laser-plasma [1]. Noticeable self-absorption of the Balmer series hydrogen alpha line occurs for electron densities of the order of one tenth of standard ambient temperature and pressure density [2]. Self-absorption measurements include the use of a doubling mirror [3, 4]. Line-of-sight emission spectra of selected diatomic molecules in air or specific gaseous mixtures at or near atmospheric pressure reveal minimal plasma re-absorption.

Abel inverted data confirm plasma expansion dynamics that unravel regions of atomic and molecular species of different electron density and temperature. Time-resolved spectroscopy determines self-absorption and self-reversal of hydrogen alpha lines in ultra-high pure hydrogen gas and in standard laboratory air that usually contains water vapor.

A Nd:YAG laser device generates the laser plasma with pulse widths in the range of 6 ns to 14 ns, pulse energies in the range of 100 mJ to 800 mJ, and for peak irradiance of the order 1 to 10 TW/cm^2. Atomic line profiles yield electron density and temperature from fitting of wavelength- and sensitivity- corrected spectral radiance data. Analysis of measured diatomic laser-plasma emission data yields excitation temperature of primarily molecular recombination spectra [5]. Applications include diagnosis of astrophysics white dwarfs [6, 7] and exoplanet spectra [8].

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Spectroscopic Diagnostics Using Line-Radiation in Laser Driven Non-equilibrium Plasmas*

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X-ray spectroscopy is used to diagnose plasma conditions in experiments at two different facilities at the Lawrence Livermore National laboratory (LLNL). First, we investigate the plasma conditions using Kr line emissions from an ignition target of an indirect drive ICF implosion on the NIF, where small traces of Kr are used as a dopant to the DD fuel gas for diagnostics. The fraction of krypton dopant was varied in the experiments and was selected so as not to perturb the implosion. Our goal is to use X-ray spectroscopy of dopant line ratios produced by the hot core to provide a precise measurement of electron temperature. Simulations of the Kr spectra in the indirect-drive exploding pusher with a range of electron temperatures and densities show discrepancies when different atomic models are used. Next, we investigate experiments performed at the Jupiter Laser Facility, where X-ray spectroscopic measurements were acquired from sub-critical-density, Ti-doped silica aerogel foams driven by a 2ω laser at ~ 5×10^{14} W/cm^2. The ultimate objective is to study the effect of an external B-field in thermally insulating the hot plasma and investigating line-radiation in multi-keV, non-equilibrium plasmas. However, the near term goal is to infer a time-integrated temperature at several positions along the laser propagation axis for several B-field cases and observe any sensitivity to density with 4.5% of Ti by atomic fraction in SiO_2 foam target. We use our non-LTE atomic model with a detailed fine-structure level atomic structure and collisional-radiative rates to investigate the Kr and Ti spectra at the estimated plasma conditions of density and temperature conditions. Synthetic spectra are generated with a detailed multi-zone, 1D multi-frequency radiation transport scheme from the emission regions of interest to analyze the experimental data and compare and contrast with the existing simulations at LLNL.

**Work supported by DOE/NNSA at NRL and U.S. DOE by LLNL under Contract No. DE-AC52-07NA27344 with partial support from the LLNL LDRD Program (Project #17-ERD-027).*

Impurities in a Magnetically Confined Fusion Reactor

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Impurities play a two-sided role for the operation of a fusion reactor plasma, as their presence dilutes the fusion fuel, i.e. a 50:50 mixture of deuterium and tritium, while the power exhaust requires also a minimum amount of seeded radiating impurities to be dealt with. Additionally, the fusion reaction produces energetic helium particles inside the plasma, providing an impurity source proportional to the plasma heating. A model describing the equilibrium state of a reactor with respect to the presence of impurities exists since the 1960s and has been elaborated in 1990 [1]. However, an appropriate evaluation of the role of the impurities with bound electrons requires atomic data such that the radiative cooling can be described with a reasonable quality. Such data was calculated in the present work for more than 35 elements, relying on codes calculating the electronic structure (MCHF), the ionization (CADW) and recombination rates (Burgess general formula) and electron impact cross sections (plane-wave Born) for more than 1000 different ions. The strength of the produced results is not linked to the employed calculation method, but rather to the fact that the data is obtained for all ionization states (some exceptions for neutrals and lowly charged species) of each element, and that for isoelectronic sequences the same sets of input configurations have been used. The resulting set of data is expected to well reproduce the experimental data at temperatures above a few 100 eV, which are typical for the confined reactor plasma.

Additionally, the simple equilibrium model [1] is extended and now handles parameterized temperature and density profiles and self-consistent fusion power performance. This extended equilibrium model has been validated by comparing it for a specific reactor design to the results of a 1D transport code with a much higher degree of detail. This extended, but still simple equilibrium model predicts impurity levels (including He) as well as the fusion power per external heating to a high accuracy. As a second step, the parameter space suited for a fusion reactor is scanned considering the estimated electrical energy production and ensuring the compatibility with technologically achievable power removal for various impurities in the reactor plasma. Using realistic boundary conditions on dilution and radiative power exhaust, a region in the parameter space best suited for a fusion reactor is identified. Based on these results, the contamination of the main plasma by low-Z impurities must be avoided. This implies that helium removal is of high importance, and that if a low-Z radiator is used in the plasma boundary, it must not leak into the main plasma.

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Soft X-ray Spectroscopy of Rare-Earth Elements in LHD Plasmas

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Soft X-ray spectra from highly charged ions of high Z rare-earth elements (lanthanides) are of great interest in terms of atomic physics issues such as configuration mixing and relativistic effects. In addition, some of the elements are potentially important in plasma applications for short-wavelength light sources. Soft X-ray spectra from lanthanide elements have been studied so far using laser-produced plasmas (LPPs), magnetically confined fusion (MCF) plasmas and electron beam ion traps (EBITs). Nevertheless, experimental surveys of the spectra are still incomplete. Also, it is worthwhile to make comparisons among the spectra from different light sources.

For this reason, we have systematically investigated soft X-ray spectra from highly charged lanthanide ions in the Large Helical Device (LHD) plasmas. Because LHD is a large-scale facility for MCF research, spectra from high Z elements in a wide range of electron temperature (up to a few keV) can be observed in an optically thin condition. Until now, all lanthanide elements except for La and Pm have already been injected in LHD plasmas [1,2]. It has already been demonstrated that the discrete and quasicontinuum spectral features from lanthanide ions with outermost N shell electrons are observed in high and low temperature conditions, respectively [2]. The discrete spectra originate mainly from ions having 4s or 4p outermost orbitals, while the quasicontinuum spectra are generated from ions having 4d or 4f outermost orbitals.

The spectra have been analyzed by various methods: several different atomic codes and/or comparisons with existing experimental data taken in different light sources. Some of the isolated spectral lines have been newly identified for the first time in LHD. It would be more difficult to construct theoretical models for the quasicontinuum feature so as to reproduce correctly the measured spectra. Nevertheless, comparisons with theoretical calculations of wavelengths and oscillator strengths lead to the assignments of some of the spectral peaks.

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Observation of Fe Kα emission spectra under keV temperature solid-density conditions

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Studies of hot dense matter from low Z elements with X-ray free electron laser motivated theoretical efforts in improved modeling [1,2] and have led to a study of highly ionized states in higher Z elements at other facilities [3,4,5]. Recently we demonstrated creation of keV temperature solid-density Fe plasma using 8 keV at LCLS and observed Kα emissions from highly ionized hot-dense Fe plasmas. In this talk, we will present nano-focusing technique providing peak intensity of 10^{19} W/cm^2 for isochoric X-ray heating and spectroscopic results and discuss electronic structure with increasing ionization.

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Comparison of x-ray sources generated from sub-ps laser-plasma interaction on clusters and solid targets

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This is an investigation of the difference between the x-ray emission of nanometer cluster targets and that of solid targets, when they are irradiated by a sub-relativistic laser pulse [1]. Special effort is made to provide comparable conditions and observables and to emphasize the specific role of target geometry. The behavior of the x-ray-emission level with respect to the laser duration shows a clear difference between target types. In solids, the x-ray-emission level monotonically increases with respect to the laser pulse duration, while an optimal duration of a few hundred femtoseconds is evidenced in clusters. The x-ray duration is determined with a time-resolved x-ray-absorption experiment through a laser-heated copper sample [2, 3]. It is observed to be one order of magnitude shorter with clusters than with solid targets.

These results are interpreted by a geometrical effect. While a solid target provides a near-critical density area for a long time, where the laser energy can be efficiently deposited, a nanometer expanding cluster very efficiently absorbs the laser energy when the critical density is crossed. Then it quickly turns into under-dense plasma where the absorption is drastically reduced. In close correlation, the spherical hydrodynamic expansion of the cluster accelerates the drop in density and temperature, which shortens the x-ray emission.

This interpretation is corroborated with numerical simulations coupling a one-dimensional hydrodynamic code (plasma heating and expansion) with a collisional-radiative code (postprocessed x-ray emission). The behavior of the x-ray emission level with the laser duration is well reproduced by calculations, as well as the measured x-ray duration, including the ability to produce sub-picosecond x-ray pulses with clusters for time-resolved applications.

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Laser Cooled Neutral Plasmas:
A Laboratory for the Study of Strongly Coupled Systems

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Strong coupling arises when interaction energies are comparable to, or exceed, kinetic energies, and this occurs in diverse systems such as dense white dwarf stars, strongly correlated electron systems, and cold quantum gases. In all environments, strong coupling complicates theoretical description and gives rise to new, emergent phenomena. Ultracold neutral plasmas (UNPs), generated by photoionization of a laser-cooled gas, are a powerful platform for studying strong coupling in classical systems, and serve as an ideal laboratory model for other strongly coupled plasmas. In this talk, I will present experimental studies of self-diffusion [1] and thermal equilibration [2] and describe the role of strong coupling in these phenomena. I will also present results from the first application of laser-cooling to a neutral plasma [3], which increases the achievable coupling strength. Although the technique we use, optical molasses, is well established, the high collision rates and rapid hydrodynamic expansion of the plasma create a unique environment for laser cooling. Through laser-cooling we have created plasmas with ion temperatures as low as 50 mK and achieved a factor of 4 enhancement in the coupling strength, allowing for experimental benchmarking of new theoretical models and molecular dynamics simulations of transport.

Research supported by the Air Force Office of Scientific Research, Department of Energy, and the National Science Foundation

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Electron-molecular cation collisions in cold plasmas

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Dissociative recombination, ro-vibrational excitation and dissociative excitation [1]:

$$AB^+(N_i^+,v_i^+) + e^- \rightarrow AB^*, AB^{**} \rightarrow A+B,\ AB^+(N_f^+,v_f^+) + e^-,\ A + B^+ + e^-,$$

where N_i^+/ N_f^+ and v_i^+/v_f^+ are the rotational and vibrational quantum numbers of the initial/final state of the target, strongly drive the charged particles' kinetics in low-temperature plasmas, as well as the production of reactive atomic and molecular species. It occurs via super-excited molecular states singly (AB*) - or doubly- (AB**) - excited, embedded in the ionization continuum of the target ion. Quantum chemistry and R-matrix techniques are used to produce the relevant potential energy states and their mutual interactions. We use these molecular structure data in methods based on the Multichannel Quantum Defect Theory [2-4] and on the Configuration Interaction ("boomerang") method [5] for computing accurate state-to-state cross sections and rate coefficients, displaying a resonant character and a strong dependence on the target's initial state. We will illustrate these features for various cations - H_2^+, BeH^+, CH^+, BF^+, N_2^+, CO^+, SH^+, ArH^+ - which enter in the composition of several plasmas in interstellar space, comets, planetary ionospheres, boundary-layers in the entries of space-crafts and close to the walls of the magnetically controlled fusion devices.

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Atomic processes at Jupiter: Ion and secondary-electron transport from swift ion precipitation into the Jovian upper atmosphere

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Understanding and control of plasma and gaseous environments, such as those in astrophysical environments, technical plasmas, and fusion energy devices, rests in large part on modeling, simulation, and diagnostics based on fundamental atomic processes. In this presentation, a description is given of recent work to provide a wide and detailed range of atomic data for inelastic processes in the interaction of swift ions precipitating into the atmosphere of Jupiter. In particular, a rich ion population exists in the magnetosphere of Jupiter, with species originating from the Galilean moons and as well from the solar wind. These populations give rise to precipitation of ions, accelerated by Jupiter's prodigious magnetic field, into the planet's upper atmosphere. Evidence of this precipitation comes directly from observations of auroral x-ray line emission in the polar regions coming from radiative de-excitation following charge transfer between the precipitating ions and atmospheric molecules.

Therefore the need exists for data describing secondary-electron production in 0.01 to 25 MeV/u O^{q+} (q=0-8) [1] and S^{q+} (q=0-16) + H_2 [2] collisions motivated by observation of the precipitation of these ions, originating largely from the volcanos of Io, into the Jovian upper atmosphere. In particular, MeV/u O and S ions slowdown in their passage through the atmosphere, produce secondary electrons, heat atmospheric molecules, lead to dissociation of H_2, and contribute to the atmospheric currents, linking the Jovian ionosphere and atmosphere. Incorporation of such data into models has been timely in light of the arrival of the NASA Juno probe at Jupiter in July 2016 with the unique orbital characteristics to enable observations of the precipitating ion populations and their interactions with the upper atmosphere.

We have also extended the data to include H^{q+} (q= -1,0,1) impact of H_2 [3] owing to the *in situ* observation by the Juno spacecraft. Particularly for protons, the consequences of the energy deposition in the Jovian atmosphere of this charged particle precipitation has not been adequately studied and requires comprehensive data not heretofore available.

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A Link between Atomic Physics and Gravitational Wave Spectroscopy

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Neutron star mergers are promising candidates for the observation of an electromagnetic (EM) signal coincident with gravitational waves. The recent observation of GW170817 [1] appears to be such an event, with gravitational waves confirmed by subsequent EM signals ranging from the infrared to x-ray portions of the spectrum. The properties of the ejecta produced during these events are predicted to play an important role in the electromagnetic transients called macronovae or kilonovae. Characteristics of the ejecta include large velocity gradients and the presence of heavy r-process elements, which pose significant challenges to the accurate calculation of radiative opacities and radiation transport. For example, these opacities include a dense forest of bound-bound features arising from near-neutral lanthanide and actinide elements. We use the Los Alamos suite of atomic physics and plasma modeling codes [2] to investigate the use of detailed, fine-structure opacities [3] to model the EM emission from kilonovae. Our simulations [4] predict emission in a range of EM bands, depending on issues such as the presence of winds, elemental composition, and viewing angle.

This work was performed under the auspices of the U.S. Department of Energy by Los Alamos National Laboratory under Contract No. 89233218CNA000001.

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Atomic processes in dense plasmas through the average-atom approach

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In this talk, we will address the calculation of cross-sections for some atomic processes, in the context of dense, coupled, plasmas.

Due to their relative simplicity of implementation, compared to more detailed models (detailed level accounting, detailed configuration accounting, etc.), average-atom models are a privileged framework for the quantum and statistical modeling of dense plasmas. They notably allow one to account for electron screening and ion surrounding using a quantum description both for bound and free electrons. This is useful in order to describe plasmas in which part of the ion orbitals are shifted towards the continuum or even pressure-ionized.

First, we will recall the specific issues of atomic modeling of dense plasmas and present a brief history of average-atom models. Then, we will describe the methods that use average-atom models in order to calculate thermodynamic properties and cross-sections of atomic processes in dense plasmas. We will see which relevant results they can provide, some of their limitations, and briefly discuss some problems that remain open, such as the modeling of fluctuations, or the accounting for channel mixing and collective phenomena in the photoabsorption.

An Effort to Reconcile Electron-Broadening Theories

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Calculations of line broadening are important for many different applications including plasma diagnostics and opacity calculations. One concern is that line-shape models employ many approximations that are not experimentally validated for most element conditions due to challenges with high-fidelity line-shape benchmark experiments. Until such experiments become available, we need to test approximations with ab-initio line-shape calculations.
There are three primary formalisms to derive an electron-broadening operator: the impact theory (Baranger, Griem), relaxation theory (Fano), and kinetic theories (Zwanzig, Hussey), all of which give different expressions for electron broadening. The impact and relaxation theories approximate the density matrix as factorizeable while the kinetic theory has a more general density matrix. The impact and kinetic theories relate the electron broadening operator to collision amplitudes, while the relaxation theory has a more complicated formula using projection operators. Each theory has a different prediction for the width and shift of spectral lines, which will become apparent in strongly-coupled plasmas.
We have made an effort to better understand the approximations and limitations of all of these approaches and to try to reconcile the differences between them. Here, we present the current status of our understanding of the electron-broadening theories and our preliminary attempt to unify the various formulae. Currently, we have found the projection operator to be necessary part of line broadening. We will be showing (for the first time) how the projection operator broadens spectral lines.

Acknowledgements
+Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.This work was supported by the U.S. Department of Energy, Office of Science Early Career Research Program, Office of Fusion Energy Sciences under FWP-14-017426.

^The work of C.F. and D.K. was carried out under the auspices of the US Department of Energy by Los Alamos National Laboratory under contract No. DE-AC52-06NA25396.

*M.H.M. and D.E.W. acknowledge support from the US Department of Energy under Grant No. DE-SC0010623, the Wooton Center for Astrophysical Plasma Properties under the US Department of Energy under Grant No. DE-FOA-0001634, and the National Science Foundation Grant No. NSF-AST 1707419

Stark-Zeeman line shapes model for multi-electron radiators in hot and dense plasmas submitted to large magnetic fields.

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We present a Stark-Zeeman spectral line shape code designed to provide fast and accurate line shapes for arbitrary atomic systems in plasmas for a large range of conditions. It is based on the coupling of the PPP code, a Stark broadened spectral line shape code [1,2], developed some years ago for multi-electron ion spectroscopy in inertial confinement fusion, and the MASCB code, recently developed to generate B-field dependent atomic physics. The latter provides energy levels, statistical weights and reduced matrix elements of multi-electron radiators by diagonalizing the atomic Hamiltonian which includes the well know B-dependent term. They are used as input in the line shape code working in the standard quasi-static ion/impact electron limit. The static ion microfield distribution is computed using the APEX model and the stochastic equation that governs the evolution of the emitter in the plasma is solved in the Liouville space by using the frequency fluctuation model [3], to introduce the corrections due to the ion dynamics effects. The physical model of the electron broadening is based on the semi-classical impact approximation including the effects of a strong collision term [4], of interference [5] and cyclotron motion [6]. As the emission is polarized, the output profiles are calculated for a given angle of observation compared to the direction of the magnetic field. We have also access to each p, s+ and s- components, so that the polarization degree can be inferred. Spectral line shape calculations have been performed for various experimental conditions. We focus here on a regime where the coupling on an external magnetic field to the atomic magnetic moment dominates the spin-orbit interaction.

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This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programs 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Observation of first resonance pumping of x-ray line profiles of highly charged ions in dense plasmas at LCLS-MEC

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Testing fundamental line shape models in hot and dense plasmas is of great interest for the atomic and plasma physics communities. For example, radiation transport, dependent of emission and absorption profiles, controls the energy balance and temperature profile in stars while opacity represents a key parameter to understand the evolution of various astrophysical objects [1].
In a first proof of principle experiment at LCLS-MEC end-station [2], we have investigated the fundamental line shape properties of emission and absorption of ions in dense plasmas.
For these purposes, we employed the XFEL self-seeded mode resonantly to scan the frequency dependence of x-ray bound-bound transitions of highly charged ions in dense vanadium plasmas created with an optical laser delivering 1.2J, 175ps pulses.
A spherically bent crystal spectrometer was setup and coupled to a PI-MTE CCD camera to provide high-spectral resolution.
We present the experimental setup and the measurement procedure used to perform the self-seeded resonant photo-pumping.
In addition, we show first results of the photo-pumped He-like Rydberg series and the influence of the scanning energy on the line profile. We have observed asymmetries in the emission and absorption profiles for x-ray transitions in He-like ions that question standard theories.

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Investigating atomic kinetics in photoionized plasma experiments using x-ray transmission spectroscopy

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We discuss an experimental effort to create and study astrophysically relevant photoionized plasmas in the laboratory. Conditions relevant to the extreme environments in x-ray binaries, accretion disks around black holes, and active galactic nuclei have long been experimentally inaccessible. Astronomers looking to understand such objects rely on the accuracy of the photoionization models they use, yet we are only beginning to have the ability to probe this regime experimentally with devices such as the Z-Machine at Sandia National Laboratories.

Our experiment employs the intense x-ray flux emitted at the collapse of a Z-pinch to heat and backlight a neon photoionized plasma contained within a cm-scale gas cell with atom number densities of 10^{17} to 10^{18} cm^{-3}. The broadband x-ray flux at the gas cell at the peak of the x-ray drive is of order 10^{12} W/cm^2 producing an order of magnitude range in ionization parameter from about 5 to 50 erg*cm/s, depending on gas filling pressure. The resulting plasma conditions are determined using K-shell line absorption spectroscopy from a KAP crystal spectrometer capable of capturing both time-integrated and time-gated transmission spectra. Analysis of these spectra yields ion areal densities and the charge state distribution, which can be compared with simulation results from atomic kinetics codes. In addition, the electron temperature is extracted from level population ratios of nearby energy levels in Li-like ions, which can be used to test heating models of photoionized plasmas as well.

This work was sponsored in part by DOE NNSA HEDLP grant DE-NA0003875, DOE Office of Science Grant DE-SC0014451, the Wootton Center for Astrophysical Plasma Properties, and the Z Facility Fundamental Science Program of SNL.

Contributed Talks

Inference of electron density in the hot spot of NIF capsules from krypton helium-β Stark line shapes

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The dHIRES (DIM based high resolution) x-ray spectrometer measures Kr Heα and Heβ spectra from NIF compressed capsules with 10-eV spectral and 30-ps temporal resolution. Theoretical calculations of the Stark-broadened line shape of the Heβ complex (unbroadened components: 3 $^3P_1$, $^1P_1$, $^1D_2$) show monotonic variations with electron density of the line widths, line energies, and intensity of the peaks associated with the lower energy 3 $^3P_1$ and higher energy 3 $^1D_2$ lines relative to that associated with the main, central energy 3 $^1P_1$ peak. Comparison of the measured Kr Heβ complex line profiles with the theoretical line shapes provides a measure of the time history of the electron density. Inferred electron densities in these preliminary investigations are in the range (2 – 7) × 10^{24} cm^{-3} and show reasonable agreement with LASNEX predictions for two of the NIF shots. These theoretical predictions of line shapes and comparisons with measured spectra will be shown for some NIF shots with Kr-doped capsules.

Work performed under the auspices of the U.S. Department of Energy by Princeton Plasma Physics Laboratory under contract DE-AC02-09CH11466 and by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344

EUV spectroscopy on highly-charged tin ions in an electron beam ion trap

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Extreme ultraviolet (EUV) light emission from highly-charged tin ions in laser-produced plasma is used in state-of-the-art nanolithography. We present EUV spectroscopy of the relevant Sn^{7+} – Sn^{20+} ions trapped in an electron beam ion trap (EBIT) at the Max Planck Institute for Nuclear Physics in Heidelberg, Germany. A matrix inversion technique is introduced to obtain true charge-state-resolved spectra from the measured experimental spectra. Accurate determination of the transitions of highly-charged tin ions is indispensable for producing high-quality atomic data to feed in opacity tables to simulate and optimize the plasma. Intriguingly, we show that the resonance transitions $4p^m – 4p^{m-1}4d$ (m=5-4) of Sn^{15+} and Sn^{16+} ions, which have not been previously investigated, contribute in the 2% bandwidth around 13.5 nm that is relevant for nanolithography.

Analysis of the Contribution of Ar Dielectronic Recombination Lines to the Unknown Faint X-Ray Feature Found in the Stacked Spectrum of Galaxy Clusters

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An exciting 2014 study [1] reported a possible dark matter signature at 3.55 keV – 3.57 keV in the stacked spectra of galaxy clusters. To help rule out possible atomic origins, we measured Ar emission from $1s^22l$-$1s2l3l'$ satellite transitions near 3.6 keV. The highly charged Ar ions were produced, trapped and excited using the electron beam ion trap (EBIT) at the National Institute of Standards and Technology. The nearly mono-energetic electron beam was scanned in 15 eV increments from 2 keV to 5 keV. X-rays were measured simultaneously with a high count rate Ge detector and a high resolution crystal spectrometer that is able to resolve features that are less than 2 eV apart at 3 keV. The collisional-radiative model NOMAD [2] was used to create synthetic spectra for comparison with both our EBIT measurements and with spectra produced with the AtomDB database/Astrophysical Plasma Emission Code (APEC) [3,4] used in the 2014 work. Excellent agreement was found between the NOMAD and EBIT spectra at each electron beam energy, providing a high level of confidence in the atomic data used. Comparison of the NOMAD and APEC spectra revealed a number of missing lines at 3.56 keV, 3.62 keV, 3.64 keV, and 3.66 keV in the APEC spectra. These features are primarily due to a lack of Be-like Ar DR data in AtomDB. At an electron temperature of T_e = 1.72 keV, inclusion of $1s2l2l'2l''$ and $1s2l2l'3l''$ data in AtomDB increased the total flux in the 3.5 keV to 3.66 keV energy band by a factor of 2. While important, this extra emission is not enough to explain the unidentified line found in the galaxy cluster spectra [5].

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The He/Ne beam diagnostic for line ratio spectroscopy in the Island Divertor of Wendelstein 7-X

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A line-ratio spectroscopy system based on thermal helium (He) and neon (Ne) collisional-radiative models (CRM) enables measurement of n_e and T_e [1] in front of the horizontal divertor target of the Wendelstein 7-X optimized stellarator [2]. The system has been successfully used in a variety of the device's magnetic configurations, including the standard 5/5 magnetic island configuration. For the second divertor campaign of the device, the observation system has been upgraded, adding 27 new vertical lines of sight to the existing 27 horizontal ones. These lines are channeled to multiple 20 cm and 32 cm Czerny-Turner spectrometers, allowing high spectral resolution observation of diagnostic helium and neon lines, as well as various visible impurity lines and Balmer series lines. Gas injection is realized via two boxes with 5 fast piezo valves each, mounted directly behind the divertor plates in one upper and one lower divertor module, which are magnetically connected in the device's standard 5/5 magnetic island configuration [3]. Helium has been used as a routine gas, while neon has been recently tested in order to extend the applicability of the diagnostic to the detached divertor regime at very low T_e (< 10eV). In this work, T_e and n_e profiles across the divertor island are shown for a variety of experimental conditions, including impurity-seeded and detached plasmas. Also presented here is an early implementation of Bayesian modeling of this diagnostic via the Minerva Framework [4].

This work has been funded by the Department of Energy under grant DE-SC0014210.
This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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Photon and Electron Impact Ionization of Ions in Warm/Hot Dense plasmas: Modifications due to the Transient Localization of Continuum Electrons

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Continuum atomic processes initiated by photons and electrons occurring in a plasma are fundamental in plasma physics, playing a key role in the determination of ionization balance, equation of state, and opacity. Here we propose the notion of a transient space localization of electrons produced during the ionization of atoms immersed in a hot dense plasma, which can significantly modify the fundamental properties of ionization processes. A theoretical formalism is developed to study the wave functions of the continuum electrons that takes into consideration the quantum de-coherence caused by coupling with the plasma environment. The method is applied to the photoionization of Fe^{16+} embedded in hot dense plasmas. We find that the cross section is considerably enhanced compared with the predictions of the existing free-atom model, and thereby partly explains the big difference between the measured opacity of Fe plasma [1] and the existing standard models for short wavelengths.

We also proposed that the transient space localization of the one electron states involved in the collision processes significantly modifies the wave functions of the scattering and ionized electrons resulting in big enhancements of these parameters. A theoretical formalism incorporating the notion of the one electron states localization is developed and applied to study the electron-ion collision processes embedded in a solid-density magnesium plasma. The results show that not only the collision dynamics and the energy correlation of the two continuum electrons are greatly modified, but also the integrated cross sections and transition rates are dramatically increased in hot dense plasmas. Compared with the results obtained by the isolated ion model, the integrated cross section can be increased by one order of magnitude and the transition rate by two orders of magnitude, which supports the recent experimental evidences that the state-of-the-art theories with the results of isolated atom model underestimate the electron impact ionization cross sections and collision rates in the solid-density Al [2] plasmas produced using X-ray free electron lasers (FEL) by more than one order of magnitude.

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“Universal” theoretical approach for determination of cross sections for dissociative recombination, rotational, vibrational, electronic excitation of molecular ions

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Plasma at relatively low temperatures, a few eV and below, contains not only atomic, but also molecular ions. This is the reason why molecular ions play an important role in plasma properties, its evolution and decay at low temperatures. Thus, it is important to take the molecular ions into account when one deals with low-temperature atomic plasma. Depending on the temperature, electronic (for T<10 eV), vibrational (T<1 eV), or rotational (T<0.0.5 eV) structure of the molecular ions should be accounted for to describe the behavior of the plasma. Measuring cross sections for different processes involving the molecular ions is difficult, especially because dozens or even hundreds of processes should be taken into account for a reasonable modeling of plasma. In this situation, plasma modeling should rely on theoretical approaches for determination of properties and cross sections of species present in molecular plasma.

It this talk, I will describe different theoretical techniques developed during the last decade to compute cross sections for different processes involving electron-molecule collisions: dissociative recombination, rotational, vibrational, electronic excitation of molecular ions, dissociative electron attachment to neutral molecules, radiative processes in electron-molecule collisions.

Spectroscopy of laser-produced lanthanum plasmas in the 0.8 – 4.2 nm region

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The results of a spectroscopic study of soft x-ray emission from highly-charged lanthanum ions generated in a laser-produced plasma will be presented. The spectrum, recorded in the 0.8 – 4.2 nm region, exhibits both line and narrowband features. In terms of the former, the main contributors to the spectrum are $\Delta n > 0$ transitions in highly-charged Ni-, Cu-, Zn- and Ga-like ions. Interestingly, flexible atomic code (FAC) calculations of these spectra predict a near-coincidence in transition energy for numerous transitions originating from neighboring isoelectronic sequences. In certain cases, this hinders our ability to make unambiguous line identifications.

In addition to discrete line features, emission in the form of narrow, quasicontinuous bands are also observed throughout this spectral range. Below 2 nm, the most intense spectral features arise from $3d^n – 3d^{n-1}4f$ transition arrays in highly-charged Fe-like ($n = 8$) and Co-like ($n = 9$) lanthanum ions. The origin of intense narrowband features located above 2 nm has been attributed to transitions of the form $3d^94l – 3d^95l'$ (where $l = 0 – 3$, $l' = 0 – 4$) between excited-state Ni-like configurations. Analogous transition arrays in Fe- and Co-like lanthanide ions may also contribute to this spectral region. Where possible, comparisons will be made with previous experimental and theoretical studies of highly-charged lanthanum ion spectra [1 - 5].

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Recent Activities in Atomic and Molecular Data at the IAEA

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The Atomic and Molecular Data (AMD) Unit [1], in the Nuclear Data Section of the IAEA, is dedicated to the provision of evaluated data on atomic, molecular and plasma-material interaction that are relevant for nuclear fusion research. In addition to hosting Technical Meetings of experts to address specific data needs, the AMD Unit also organizes 3 – 4 year long Coordinated Research Projects (CRPs) to facilitate collaborative research between 10 – 15 research groups with the aim of producing and evaluating data within a focused domain. Ongoing CRPs that will be discussed are:

- *Data for Atomic Processes of Neutral Beams in Fusion Plasma* (2017 – present) [2]
- *Atomic Data for Vapour Shielding in Fusion Devices* (2019 – present) [3]

The AMD Unit has also initiated the Global Network for the Atomic and Molecular Physics of Plasmas (GNAMPP) [4], a consortium of research groups working in the area of fundamental atomic and molecular physics relevant to plasma processes. In bringing together theoreticians, experimentalists and fusion plasma modelers, GNAMPP provides a forum for the evaluation, validation and dissemination of data, the benchmarking of relevant modelling codes and the formulation of research guidelines and priorities.

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Development of High Fluence X-Ray Sources Using Laser Heated Novel Nano-Wire Metal Foams

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High fluence multi-keV x-ray sources (E_{photon} = 1 - 20 keV) are needed for a variety of high energy density (HED) research applications. Laser heated free standing metallic nano-wire foams have been found to be a promising x-ray source candidate and have been in development for the past few years. The targets are fabricated by casting the metal nano-wires in a mold of the appropriate shape and size. Nano-wire foams of Cu (Z = 28; $E_{K\text{-shell}}$ ~8.5 keV) and Ag (Z = 47; $E_{K\text{-shell}}$ ~23 keV) have been successfully fabricated into cylindrical targets having densities of 6–20 mg/cc. These densities put the plasma electron densities below the critical density for laser absorption making the targets underdense. Therefore, the laser light can be fully absorbed by the bulk material of the target and produces a volumetric radiator.

Obtaining these high fluences at the higher K-shell photon energies ($E_{K\text{-shell}}$) is challenging. The higher $E_{K\text{-shell}}$ emission requires higher atomic number materials. The electron temperatures needed to create the K-shell emission increases with atomic number. For example, electron temperatures greater than 10 keV are needed for the silver nano-wire foams. Achieving the required electron temperature for a given atomic number requires an increasing amount of laser power and energy.

Therefore, 192 laser beams from the National Ignition Facility (NIF) laser are used to heat the nano-wire foams with ~400 TW of 351 nm laser light in a 2.5 ns square pulse in time depositing ~950 kJ into each nano-wire foam. The NIF targets consist of Ag nano-wires in the shape of cylinders nominally 4 mm in diameter and 4 mm tall. Metrology has found that the nano-wire foams consist of 51% silver by atomic fraction. The remaining mass are various hydrocarbon compounds.

The K-shell x-ray emission and the resulting x-ray environments are characterized by using the x-ray diagnostics at NIF. X-ray conversion efficiency from these laser heated underdense Ag nano-wire foams have been measured to be ~0.6% which is about twice that observed in more conventional laser heated cavity x-ray sources. Measured high resolution spectra indicate that a significant amount of the K-shell emission is from the He-like charge state. Experimental results and comparisons with simulations will be presented.

This work was done under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. DE-AC52-07NA27344

Molecular Data for Hydrogen Plasma Modeling

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Low-temperature hydrogen plasmas are ubiquitous throughout the Universe. They exist in fusion plasmas, solar atmospheres, planetary atmospheres, primordial gas clouds, and determined much of the chemistry of the early Universe. To model these plasmas in local thermodynamic equilibrium (LTE) and non-LTE requires the constituents energy levels, transition cross sections or rate coefficients to calculate populations (for non-LTE plasmas), opacities, and emissivities.

Recently we have embarked on the projects of calculating electron- and photon-molecule data of important diatomics utilizing first-principle approaches [1-3]. Here we present a wide-variety of results required to model LTE and non-LTE plasmas containing hydrogen molecules H_2, its ions H_2^+, and the isotopologues. For example, we will present electron- and photon-molecule cross sections, the molecular emission spectra of LTE plasmas at various temperatures, and preliminary results of low-temperature hydrogen plasma equations of state [4].

To model electron-molecule collisions we have developed the molecular convergent close-coupling (MCCC) method [1,2]. Results from these studies are the first of their kind: calculating cross sections over a broad range of impact energies and explicitly demonstrating convergence of the cross sections. Generally, the results are in good agreement with experiments, however, for some important processes large discrepancies are seen with generally “accepted” and used data. Subsequent new experiments have confirmed the MCCC predictions [5].

For the photon-molecule project, we have recently developed a self-consistent approach with the goal of calculating comprehensive opacity tables that are accurate across the entire range of temperature space. We have calculated cross sections, rate coefficients and the emission spectra of H_2^+ [3] and H_2, as well as investigated isotopic effects, and the effect of including electronically excited states in the emission calculations.

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Polarization of K-shell x-ray transitions in highly charged ions of Ar

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We report x-ray polarization measurements performed at the NIST electron beam ion trap [1], using two Johann-type curved crystal spectrometers equipped with Si(111) crystals, their dispersion planes oriented parallel and perpendicular to the beam direction. The photon emission in the energy range of about 3.06 keV to 3.18 keV covering the resonance line of He-like argon and its dielectronic satellite lines in Li-like and Be-like ions was recorded using both spectrometers. Polarization of x-ray transition $1s^2 - 1s2l$ lines in He-like Ar were measured at 4 keV and 8 keV while Li-like Ar ($1s^2 2l - 1s2l2l'$) and Be-like Ar ($1s^2 2l2l' - 1s2l^2 2l'$) satellite lines were observed at electron beam energies between 2.25 keV and 2.38 keV in 10 eV intervals.

The analysis of the measured spectra was based on the collisional-radiative (CR) modelling using NOMAD code [2] with magnetic-sublevel atomic kinetics. The CR model included configurations with single electron excitations up to n = 5, and autoionizing states with single K-shell electron excitations to n = 3 for H-like to Be-like ions. The model considered the basic atomic processes for magnetic sublevels such as radiative decay rates, excitation (de-excitation) and ionization (3-body recombination), and autoionization and dielectronic capture. The corresponding cross sections and probabilities were determined using the Flexible Atomic Code (FAC) [3]. The polarizations calculated with the magnetic-sublevel CR model were also compared with the results obtained within the density matrix formalism [4]. Comparison of the two theoretical methods points out the importance of radiative cascades for the $1s^2 - 1s2l$ lines in He-like Ar. The details of the theoretical approach and the comparison with experimental results will be presented and discussed.

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Scaling of emission efficiency and optical depth in dense 1µm-laser-driven Sn plasmas

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Laser-produced plasmas from tin micro-droplets are efficient sources of extreme ultraviolet light finding application in state-of-the-art nanolithography. Tin is an ideal fuel for these sources because of its serendipitous electronic structure where a broad range of charge states from Sn^{8+} to Sn^{15+} have multiple configurations which radiatively decay within an industrially relevant 2% bandwidth around 13.5nm.

The dense nature of these laser-produced tin plasmas, in particular when driven with 1µm laser light, gives rise to opacity related broadening of the spectral emission outside of the utilizable 2% bandwidth. We experimentally investigate the influence of changes in laser intensity, laser pulse duration and size of the liquid tin droplet on the spectral emission of the plasma and its efficiency in emitting EUV light using a 1µm drive laser. To capture the efficiency in radiating EUV light a geometrical model is employed featuring a characteristic plasma scale length. Observed spectral broadening with increasing laser pulse duration or droplet size is connected to the relative optical depth of the plasma using an analytical model for radiation transport in a homogeneous, thermal plasma.

Posters

NIST Atomic Databases and Online Tools for Plasma Physics

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The National Institute of Standards and Technology (NIST) provides a number of online standard reference databases of atomic properties [1]. The most widely used of them is the Atomic Spectra Database (ASD) containing data on energy levels, ionization energies, wavelengths, and transition probabilities of spectral lines. Among many other applications, these data are widely used in plasma modeling. In 2017, we introduced a new online interface for modeling and diagnostics of plasma pertinent to laser-induced breakdown spectroscopy (LIBS) [2]. This user-friendly interface allows generation of synthetic LIBS spectra for plasmas of arbitrary composition with specified rough initial estimates of observational parameters, such as electron temperature and density, wavelength range, and spectral resolution. Initial Saha-Boltzmann modeling is made on the server side, and all relevant data, such as spectral lines and energy levels data are transmitted to the user's computer, which plots the simulated spectrum. Then it is possible for the user to change the appearance of the plot by zooming in and out or selecting graphs for individual species and recalculate the simulated spectrum with modified parameters. In addition, the user can load an experimental spectrum into the same plot and compare it with the simulation. Besides that, NIST hosts other online computational tools, such as the plasma-kinetics code FLYCHK [3]. This code provides a capability to generate atomic level populations and charge state distributions for a wide range of elements under NLTE conditions.

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Atomic Data for Modeling the Fe K-Lines in High-Density Astrophysical Plasma Environments: Radiative, Auger and Photoionization Processes

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Iron X-ray K-lines emitted by black hole accretion disks play an important role in astrophysics. Indeed, they have observed widths and shifts that imply an origin very close to the central black hole [1]. They can give information about the effects of special and general relativity in the emitting region. Moreover, some important properties of the black hole itself, such as its spin, can be inferred by modeling the distortion of the Fe K emission profile [2]. Plasma conditions in accretion disks are thought to be characterized by electronic densities as high as 10^{22} cm^{-3} [3]. Such conditions may affect the atomic processes corresponding to the ionic species present in the plasma. However, atomic data used in the standard programs to model astrophysical X-ray spectra are computed assuming an isolated ion approximation. Therefore, this shortcoming is thought to be the major reason for the inconsistencies observed in the results [4].

The main goal of the present work is to estimate the effects of high-density plasma environment on the atomic processes involving the K-vacancy states in iron ions. For this purpose, relativistic atomic structure calculations have been carried out using the multiconfiguration Dirac-Fock (MCDF) method, in which a time averaged Debye-Hückel potential has been considered, using the GRASP92 [5] and of the RATIP [6] codes. In this contribution, we present some results concerning the influence of plasma environment on the radiative, Auger and photoionization processes in highly-charged iron ions.

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Poster #3

Quantifying the Statistical Noise in Computer Simulations of Stark Broadening

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In plasma spectroscopy, the shape of an atomic line is determined by the perturbation of the energy levels due to the charged particles surrounding the emitter or absorber under consideration. This is the celebrated Stark broadening problem. It still has no solution, in the sense that no general formula has been found for a line shape relative to an arbitrary atomic species. The Dyson series, which provides a solution to the time-dependent Schrödinger equation, is only a formal relation hardly applicable to calculations in realistic conditions. The computer simulation technique has been developed in the seventies with the purpose of reproducing the exact solution as closely as possible based on a Monte Carlo technique [1]. Essentially, a simulation consists in numerically integrating the time-dependent Schrödinger equation that governs the dynamics of an atom perturbed by a fluctuating electric field, itself being generated from a numerical integration of the Newtonian equations of motion for the charged particles moving at the vicinity of the emitter. The initial conditions for the perturbers are generated randomly and, due to this, the numerical line shape exhibits a noisy behaviour, which can be reduced only by increasing the number of runs. In this work, we examine the sensitivity of the results to the statistical noise. We address the speed of convergence of the spectrum. A focus is put on hydrogen line shapes due to the simplicity of the atomic data they involve. Applications to spectra in magnetic fusion plasmas are performed as an illustration.

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Spectrum of Ni V in the Vacuum Ultraviolet

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We will be presenting our recent assessment of Fe V and Ni V in the VUV. This presentation will demonstrate the major improvements that we made to the atomic data available for Ni V and that our work substantiates previous assessments of Fe V. Our work contains 97 remeasured Fe V wavelengths (1200 Å to 1600 Å) and 123 remeasured Ni V wavelengths (1200 Å to 1400 Å) with uncertainties of approximately 2 mÅ. An additional 67 remeasured Fe V wavelengths and 72 remeasured Ni V wavelengths with uncertainties greater than 2 mÅ are also included. These new measurements, conducted at the National Institute of Standards and Technology, reduce the uncertainties of Ni V wavelengths by roughly a factor of four in most cases. A systematic calibration error was also identified in the previous Ni V wavelengths (1100 Å to 1300 Å) and was corrected in our work. In addition to new wavelength data, we also conducted a radiometric calibration of our spectra to provide calibrated intensity values for our Ni V wavelengths. Additionally, a new energy level optimization, based on our new measurements of Ni V, is presented that includes Ni V level values as well as Ritz wavelengths.

Our work improves upon the available data used for observations of quadruply ionized nickel in white dwarf stars. In particular this compilation is targeted towards observations of the G191-B2B white dwarf spectrum that has been used to test for variations in the fine structure constant, α, in the presence of strong gravitational fields [1]. The laboratory wavelengths for these ions were thought to be the cause of inconsistent conclusions regarding the variation limit of α as observed through the white dwarf spectrum. These inconsistencies can now be addressed with our improved laboratory data.

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Plasma Conditions in Short-Pulse-Heated Buried Tracer Layers from Fine-Structure X-ray Emission

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A quartet of high-resolution x-ray Bragg crystal spectrometers was deployed at the Titan laser to measure x-ray self-emission from laser-heated Ti and Mn layers in Al foils. Targets were produced via sputtering with thin (0.1–1 μm) layers of mid-Z tracer elements sandwiched between 15 μm Al foil and a thin Al tamp (0–4 μm). When exposed to the relativistic-intensity laser pulse, the target heats comparably to an undoped Al foil if the tracer layer is sufficiently thin. It is only this thin layer that emits fine structure x-rays within the bandwidth of the crystal spectrometers. By shooting a set of targets with varied tracer element (Ti, MnAl, or both), tracer thickness, and tamp thickness, the time-integrated x-ray flux can be measured at many localized depths in the target. These high-resolution fine structure spectra of He- and Li-like Ti and Mn are observable due to focusing spherical crystal forms that enhance signal-to-noise ratio on time-integrating detectors [1]. The dispersed x-ray spectra are compared to collisional-radiative (CR) codes [2,3], implying plasma conditions within each emitting layer. The spatially-resolved, emissivity-weighted plasma parameters provide important benchmarks for hydrodynamic and fast-electron energy transport codes. In addition, the x-ray spectra challenge CR calculations to match line intensities, ratios, widths and shapes, and to explain discrepancies between codes and data [4].

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Wavelengths, Energy Levels, Hyperfine Structure and Oscillator Strength Measurement of Sc I and Sc II

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The precise observation of Sc-Ar, Sc-Ne and Sc-Ge hollow cathode emission spectrum have been made in the region 185−3500 nm (54,055 cm^{-1} − 2857 cm^{-1}) by Fourier transform (FT) spectroscopy, and in the region 80−410 nm (125,000 cm^{-1} − 24,390 cm^{-1}) using a 10.7 m grating spectrograph at National Institute of Standards and Technology (NIST). We measured more than 1650 lines in Sc I and Sc II and used them to derive optimized values for 240 energy levels. The measurements using FT spectroscopy show significant hyperfine structure (HFS) patterns for more than 300 lines. These were fitted using the computer package XGREMLIN [1] to determine the magnetic dipole hyperfine interaction constant A for 102 levels, of which 57 have no previous HFS constants. We also determine approximate electric quadruple HFS constant B for several levels. The same spectra were used to measure the branching fractions and transition probabilities for 258 lines in Sc I and Sc II [2] and combined with new complete HFS component patterns from HFS constants to redetermine the Sc abundance in the Sun, Arcturus, and the MP halo star HD 84937.

This work was partially supported by NASA awards NNH17AE08I (GN) and NNX16AE96G (JEL), and NSF grant AST-1516182 (JEL).

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Prospects concerning 1D photonic crystals in the X-ray range

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It has been demonstrated that X-ray free-electron lasers (XFELs) allows to create strong population inversion by removing sufficient core-electrons in the atoms of a medium [1,2]. This results in a “stimulated” fluorescence.

Besides this, using an adequate multilayer material allows one to obtain a resonant standing-wave inside the material, which is equivalent to the use of a cavity [3,4,5].

We present here a prospective study of the diffraction of stimulated emission inside a periodic structure, in the x-ray range. For that purpose, we present here a theoretical study of the interaction of monochromatic x-ray photons with a bulk multi-layer sample and, of the resulting “stimulated” fluorescence. X-ray energy deposition (and pumping) as well as fluorescence, are modeled through a calculation of the radiation field in the material, which in turn depends on the complex refraction index linked to a complex NLTE atomic physics [6].

Different case-calculations of the diffracted K_α fluorescence are discussed. In particular, one discusses the possibility of enhancing fluorescence by using the periodic structure as a resonator (1D photonic crystal).

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Poster #8

X-ray Observations of Ne-like Xe from C-Mod Tokamak Plasmas

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X-ray spectra in the wavelength range from 2.70 to 2.76 Å from xenon in near neon-like charge states have been observed in Alcator C-Mod tokamak plasmas with a spatially imaging high resolution spectrometer. The 3D line ($2p^6 - (2p^5)_{3/2}3d_{5/2}$) ~2.72 Å has been identified, along with nearby Na- and Mg-like satellites. The intensity ratio of 3D to the Mg-like line satellites near 2.74 Å increases strongly with electron temperature in the range from 3 to 4 keV. Wavelength calibration was obtained from nearby He-like Kβ calcium transitions. Implications for the ITER x-ray spectrometer will be discussed.

Investigation of radiation and dynamics properties in laser-produced plasma

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The radiation and dynamic properties of laser-produced plasmas are studied both experimentally and theoretically. Firstly, the emission spectra of plasma have been measured by using a spatio-temporally resolved emission spectroscopy technique. Meanwhile, we present a radiation hydrodynamics model based on the conductive heat transfer in the condensed phase, radiative gas dynamics, and laser radiation transfer in the plasma as well as surface evaporation and back condensation at the phase interface. Moreover, calculation of the ionization balance and the charge states is respectively performed within the time-dependent collisional radiative model (CRM).

By using the radiation hydrodynamics model, the contour images of Si plasma temperature at 20-70 delay times are shown in figure 1. The color gradient represents the change of the plasma temperature. It can be clearly seen that with the increase of the delay time, the contour of the plasma gradually decreased, the corresponding plasma temperature from near the target surface 25 eV fast decay to 16 eV. From the plasma core to the edge, there is a clear plasma temperature gradient, it is confirmed that the plasma is highly inhomogeneous and transient.

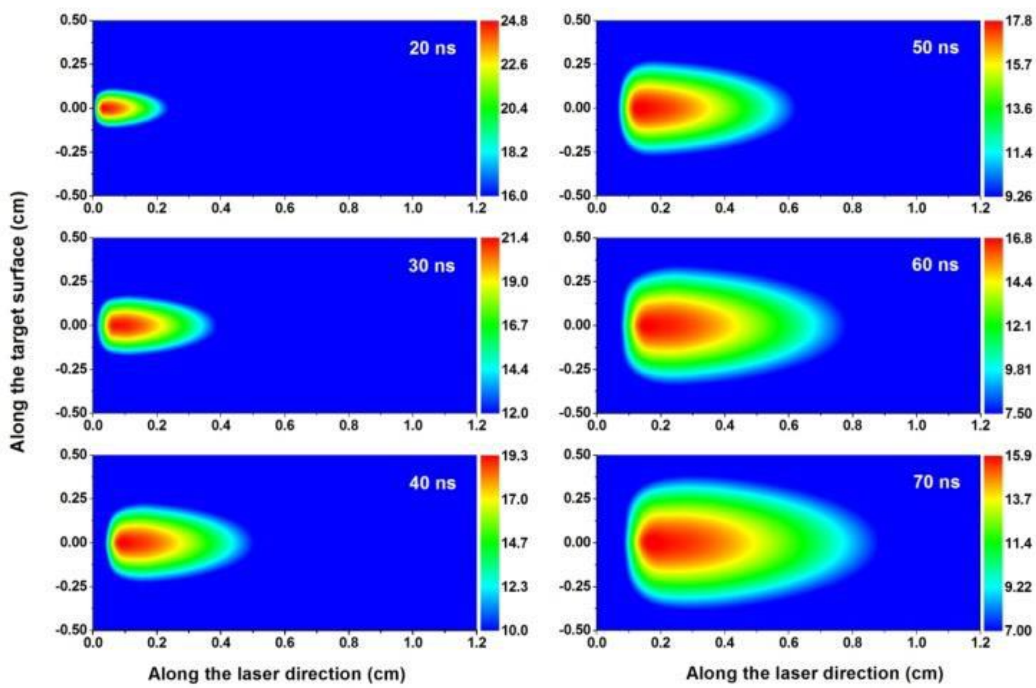

Fig. 1. The temporal evolution of temperature in the silicon plasma

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New Prism EOS and Opacity Tables with NLTE Atomic Kinetics
(*contributed talk*)

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We present new features of PROPACEOS, a code that generates equation-of-state (EOS) and opacity tables for radiation-hydrodynamics and spectroscopic simulations. In addition to existing capabilities to produce tables for LTE and optically thin NLTE plasmas, these new features allow PROPACEOS to perform calculations that include other effect of NLTE atomic kinetics. The primary purpose of this development is to facilitate efficient spectroscopic simulations for short-pulse laser experiments. The simulations are based on post-processing of PIC calculations and focus on the analysis of K-alpha/K-beta emission signatures. PROPACEOS can now produce emissivity and opacity databases on a grid with up to six independent parameters, for example: plasma temperature, plasma density, and hot electron parameters. Hot electron distributions are specified in terms of analytic functions [1]. We will also discuss new capabilities that allow for computing opacities for optically thick NLTE plasmas. We will present simulation results relevant to ongoing experiments on Omega EP laser facility.

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Poster #11

Free-Electron Degeneracy Effects for Collisional-Radiative Codes

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Collisional-radiative (CR) codes are increasingly being called upon to model conditions at high densities and low temperatures where electron degeneracy becomes important. Experiments at large laser facilities and X-ray free electron lasers routinely produce such conditions and an accurate treatment of degeneracy effects is important to their simulation and interpretation.

Degeneracy affects all processes involving one or more free electrons, including collisional excitations and ionizations, radiative recombination, auger processes and bremsstrahlung. We review the modifications necessary for a CR code to incorporate these effects. For thermal electron distributions, we present simple analytical expressions which capture or approximate the additional factors required for transition rates and radiative properties. The expressions for collisional excitation and ionization factors correct results previously published by the authors. For cases of strong degeneracy, the analytical expressions for collisional ionization and three-body recombination lose accuracy and numerical integrations require careful evaluation. For these, we present robust numerical formulations and provide a simple modification to the analytical expressions which restores accuracy.

This work performed under the auspices of U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

A Miniature Dual-anode Electron Beam Ion Trap to Generate Highly Charged Ions with Low Ionization Threshold

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In addition to their importance in hot plasma diagnostics, recent theoretical studies indicate that certain highly charged ions (HCIs), such as Pr^{9+} and Nd^{10+}, are potentially useful for such applications as the development of next-generation atomic clocks, quantum information processing, or the search for variation in the fine-structure constant [1]. Highly-stripped heavy ions have been studied in an electron beam ion trap (EBIT) with a strong magnetic field (~ 3 T). However, there are many interesting charge states that are not generated efficiently in an EBIT because of their low ionization threshold; in such cases, a lower magnetic field and more compact geometry are better suited for abundantly producing the above-mentioned examples, as well as other ions with relatively low ionization thresholds (50 eV to 1000 eV). We present a room-temperature miniature EBIT (mini-EBIT) with a dual-anode electron gun, which has been developed to alleviate the space-charge effects in propagating an electron beam at lower energy. This work discusses the tests and new capabilities of the mini-EBIT apparatus for the production and extraction of highly charged ions with low ionization thresholds. Time-of-flight spectra of extraction of noble gas HCIs (ions of Ne, Ar, Kr, Xe gases) are analyzed for the identification of ion species and the ion counts. Progress on the extraction of charge-state-selected HCI species via a Wien filter unit is presented. Preliminary design work for the re-trapping and isolation of HCIs in a permanent magnet Penning trap with a trap center magnetic field (~ 0.72 T) is also presented.

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Capture of highly charged ions in a hyperbolic Paul trap

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Confinement of ions in a trap have interesting applications, including precision spectroscopy, quantum metrology, as well as collective behaviors in strongly-coupled one-component plasmas. In most cases, singly-charged ions or few-times-ionized species are created *in situ* within the trap. However, certain applications require a dedicated, external ion source. For instance, ion beams are injected into linear radio-frequency (RF) traps to form space-charge dominated nonneutral plasmas for experiments designed to simulate the propagation of intense charged particle beams, such as found in heavy ion fusion reactors, spallation neutron sources, and high energy physics.

The isolation of highly charged ions (HCIs) is made more involved by the stronger space-charge effects, which are proportional to the square of the charge state. In this work, we report the capture of ~500 Ne^{10+} ions in a hyperbolic RF trap. Highly charged ions are extracted from an electron beam ion source/trap (EBIS/T) at NIST, and subsequently guided by a 7 m long beamline to an ion trap apparatus; a charge-to-mass analyzer nested within the electrostatic beamline optics is used to select a single charge state (Ne^{10+}) to be recaptured in the RF trap. We discuss the experimental optimization and compare the results with computational simulations. An experimental capture efficiency of ~20% was attained, capturing ~500 Ne^{10+} ions in the hyperbolic RF trap, comparable to that attained in a unitary Penning trap [1]. The larger optical access available in an RF trap is advantageous for improving spectroscopic experiments. Due to heating by the RF-driven micromotion and the absence of any cooling mechanism, the observed storage lifetime of 69 ms for the Ne^{10+} ions stored in the RF trap is shorter than the corresponding storage lifetime in the unitary Penning trap. Nevertheless, this can be useful for a variety of spectroscopic experiments, including atomic state lifetime measurements for many charge states. Possible improvements for increasing the number of captured ions and storage lifetime are explored.

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Poster #14

Time-Resolved Measurements of the Hot Spot Density and Temperature on the National Ignition Facility

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The electron density and temperature and their evolution in the hot spot of a Kr-doped, big-foot implosion target were measured for the first time using an absolutely calibrated, streaked, high-resolution x-ray spectrometer DHIRES on the National Ignition Facility (NIF) [1]. Kr Heα and Heβ complexes near stagnation were recorded on a streak camera with a temporal resolution of ~30 ps, with signal levels provided by a simultaneous time-integrated measurement on the image plate. The electron density was inferred through stark-broadened line shapes and the temperature was derived from the relative intensities of dielectronic satellites. This presentation will present first experimental measurements of Kr spectra for big-foot implosions [2], with and without W dopant in the ablator. The measurements are compared with hydrodynamic simulations using Lasnex [3], as well as collisional-radiative calculations for line intensities and shapes using Cretin [4].

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Work performed under the auspices of the U.S. Department of Energy by Princeton Plasma Physics Laboratory under contract DE-AC02-09CH11466 and by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344

Poster #15

D-line doublet observations of Na-like ions

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We present simultaneous measurements of the *D*1 (3s-$3p_{1/2}$) and the *D*2 (3s-$3p_{3/2}$) transitions in Na-like ions of yttrium [1], zirconium, niobium, molybdenum, praseodymium, neodymium, rhenium, osmium, and iridium. The highly charged species were created using the NIST electron beam ion trap (EBIT) [2] and the spectra were recorded with a flat-field grazing-incidence extreme ultraviolet (EUV) spectrometer [1]. The collisional-radiative (CR) modelling code NOMAD [3] aided the line identification measurements of these $\Delta n = 0$ transitions. The CR model uses a realistic non-Maxwellian electron energy distribution applicable to the EBIT and input atomic data from the FAC [4]. We show comparisons of the experimental wavelengths to those determined from relativistic many-body perturbation theory (RMBPT) [5] and *S*-matrix QED calculations [6]. Our experimental wavelengths agree with both theories overall, with deviations occurring at higher Z values. These comparisons test the accuracy of the calculation of QED corrections for the sodium isoelectronic sequence at high Z values, where experimental observations are lacking. In addition to the Na-like *D*-doublet observations, we also report measured wavelengths for transitions arising from the Si-, Al-, and Mg-like charge states of these ions.

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Effects of Dielectronic Recombination in Astrophysical Plasmas: Reflection Spectrum of a Black-Hole Accretion Disk

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In the context of the abundance problems in black-hole accretion disks [1], we are currently involved in a project to estimate plasma environment effects on the atomic structure and radiative parameters associated with the K-vacancy states in ions of the oxygen and iron isonuclear sequences [2−5]. These computations have been performed in the multiconfiguration Dirac−Fock framework, whereby the plasma screening is modeled with a Debye−Hückel potential. We are also interested in the plasma effects caused by the density attenuation of dielectronic recombination (DR) as recently reported by [6,7]. Their convenient analytic expressions are being incorporated in the atomic database of the XSTAR modeling code [8]. Parallelly, by eliminating the metal DR contribution in the XSTAR atomic database, we are also studying the DR manifestations in the ionization-parameter−temperature plane ($-3 \le \text{Log}\ \xi \le 3$; $-3.5 \le \text{Log T} \le 7.5$) of a plasma with solar abundances. In the present report we discuss the impact of eliminating DR on the heating and cooling rates, thermal temperature, and ionization fractions, particularly at (Log ξ, Log T) = (1.,6.) where the higher Fe average ionic charge leads to a heating rate lower by a factor of ~2.5. The effects of eliminating DR in the reflection spectrum of a black-hole accretion disk are also discussed.

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Simplified model to treat the dissociative electron attachment of complex molecules

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We present a theoretical approach to evaluate cross sections for dissociative electron attachment to polyatomic molecules. Starting from the Bardsley-O'Malley theory developed for diatomic targets, we extend the formalism of resonant scattering to polyatomic molecules. Variation of resonance energies with respect to normal coordinates of the molecules allows us to introduce a generalized dissociation coordinate. Using the local complex potential model, the present *ab inito* model gives a reasonable estimate for dissociative attachment cross sections with modest computational efforts. The model is applied to the H_2CN and NO_2 molecules. The former molecule is considered as a precursor in the formation of the CN^- anion observed in the IRC +10216 carbon star. The computed rate coefficient suggests that the dissociative electron attachment of H_2CN may not be an efficient reaction to form CN^- in the circumstellar envelope of IRC +10216. The NO_2 molecule is important in depollution of combustion and in decontamination of food. The obtained cross section for NO_2 agrees well with experimental results.

This work was supported by the National Science Foundation Grant No. PHY-1806915

Observation of Indirect Ionization of W^{7+} in EBIT plasma

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Based on the previous study by Mita *et al.*[1], the spectra of W^{7+} are measured in the visible and EUV range at SH-HtscEBIT[2] under extremely low electron beam energy conditions. The 574.49(3) nm M1 line of W^{7+} is observed at the nominal electron beam energy of 59 eV which is below the ionization energy of W^{6+}. The multi-configuration Dirac-Hartree-Fock calculation further confirms the identification of this line. A hypothesis of charge-state evolution from W^{5+} to W^{7+} is proposed, based on our theoretical studies on the energy levels of these charge states, in order to explain the appearance of W^{7+} spectra. Indirect ionization via cascade excitations from the long-lived metastable states of lower charge W ions play a key role in occurrence of W^{7+}. In addition, the EUV spectra at 75 eV as well as the FAC calculations also prove that W^{7+} appears 2 charge states in advance according to the ionization energy.

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Collisional Radiative Model for Zn laser produced plasma

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Smijesh et al. [1] have recently reported time and space resolved spectral measurements of neutral Zn emission from an ultrafast laser produced plasma, generated by the irradiation of a Zn target with laser pulses of 100 femtoseconds duration, carried out in a broad ambient pressure range of 0.05 to 100 Torr. They have obtained the plasma parameters viz. electron temperature (T_e) and electron density (n_e) from their measured optical emission spectra using simple local thermodynamic equilibrium (LTE) model. Thus, it would be interesting and worth developing a detailed collisional radiative (CR) model to obtain the reliable plasma parameters from the spectral analysis of laser produced Zn plasma (LPZP).

In the present work, we develop a detailed CR model in the light of the LPZP emission measurements of Smijesh et al. [1]. In such plasma, the electron impact excitation of Zn is a dominant process and for the modeling purposes the excitation cross sections for the various fine structure transitions involved among ground state and excited states. However, very few studies reported the electron impact excitation cross sections of Zn. Mostly these are available for the transition from the ground state ($4s^2$) to the 4s4p excited state [2]. Consequently, we first find out, the electron excitation cross sections of neutral zinc using fully relativistic distorted wave (RDW) theory [2] for several transitions involving the ground and excited states. Further, calculated cross sections are incorporated in the CR model and evaluate the plasma parameters.

In the present, CR model 30 fine structure levels have been included along with the ground state of Zn and Zn^+ which are interconnected through collisional and radiative transitions occurring in the plasma. The model incorporates various population transfer kinetic processes among fine structure levels such as electron impact excitation, ionization and radiative decay along with their reverse processes e.g. electron impact de-excitation and three body recombination [3]. The plasma parameters viz. electron density (n_e) and electron temperature (T_e) are evaluated for the pressure range 0.05-10 Torr and at 2.0 mm distance from the target surface. The details of the excitation cross sections results along with the CR model results will be presented in the conference.

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Systematic measurements of opacity dependence on temperature, density, and atomic number at stellar interior conditions (*invited talk*)

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Model predictions for iron opacity are notably different from measurements performed at matter conditions similar to the boundary between the solar radiation and convection zones [J.E. Bailey et al., *Nature* **517**, 56 (2015)]. The calculated iron opacities have narrower spectral lines, weaker quasi-continuum at short wavelength, and deeper opacity windows than the measurements. If correct, these measurements help resolve a decade old problem in solar physics. A key question is therefore: What is responsible for the model-data discrepancy? The answer is complex because the experiments are challenging, and opacity theories depend on multiple entangled physical processes such as the influence of completeness and accuracy of atomic states, line broadening, contributions from myriad transitions from excited states, and multi-photon absorption processes. To help determine the cause of this discrepancy, a systematic study of opacity variation with temperature, density, and atomic number is underway. Measurements of chromium, iron, and nickel opacities have been performed at two different temperatures and densities, and the opacity analysis method has been substantially improved. The collection of measured opacities provides constraints on hypotheses to explain the discrepancy. We will discuss the new analysis method, implications of measured opacities, experimental errors, and possible opacity model refinements.

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