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Atomic Processes in Plasmas

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BOOK OF ABSTRACTS

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The APiP meetings started in 1977 as one of the American Physical Society Topical Conferences. Since 2007 the APiP conferences have been referred to as "International", so as to better reflect the true nature of the meetings. 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 theoretical and experimental works presented at the APiP meeting are expected to contribute to new developments and applications in the topics below.

More information on the history of the APiP conference series is available from the NIST Physical Measurement Laboratory webpages.

TOPICS

- Low Temperature Plasmas: LTP
- High Energy Density Plasmas: HEDP
- Warm Dense Matter: WDM
- Astrophysical and Atmospheric Plasmas: AAP
- Magnetized Plasmas: MAG
- Atomic Data and Processes: ADP
- X-Ray Sources: XRS

The scientific program of the 2016 conference consists of invited talks, oral contributions and posters.

New in APiP meetings: On Monday, April 4, a series of six lectures will be given by world-leading scholars in the field of atomic processes in plasmas. These lectures are intended for PhD students, postdocs and more generally for young conference participants.

A TRIBUTE TO CLAIRE AND JACQUES BAUCHE

Claire and Jacques Bauche
Campus Les Cordeliers, Paris
April 2016

On Thursday 7th, a tribute will be paid to Claire and Jacques Bauche for their pioneering role in the development of complex atom physics.
Claire and Jacques proposed a proper statistical approach for analyzing the complex level-structure and spectra of open-shell many-electron atoms.
Applied to hot plasmas, their remarquable work had many developments. Many of their methods are now widely used for computing the radiative properties of hot plasmas.
In this context, some of their collaborators will present these important contributions.

Table of contents

ATOMIC DATA AND PROCESSES. I **1**

ADP.I1: Atomic data quality and needs for collisional-radiative modeling
Yu. Ralchenko 1

ADP.I2: Atomic processes in X-ray free electron produced plasmas
H. K. Chung, M. Chen, O. Ciricosta, S. Vinko, J. Wark and R. W. Lee 3

ADP.O1: Electron-impact excitation and photoionization cross-sections involving low ionization stages of Cobalt for astrophysical plasmas
N. B. Tyndall, C. A. Ramsbottom and C. P. Ballance 4

ADP.O2:Spectroscopy of highly charged iron ions relevant to astrophysical plasmas
S. Ali, E. Shimizu, T. Tsuda, H. A. Sakaue, D. Kato, I. Murakami, H. Hara, T. Watanabe, and N. Nakamura 5

ADP.O3:Atomic data and spectral models for low ionization Fe-peak ions
M. Bautista, J. Nolte, C. Mendoza, V. Fivet, C. Ballance, P. Quinet and T. R. Kallman 6

HIGH ENERGY DENSITY PLASMAS. I **7**

HEDP.I1: Prospect of photo-pumping experiment with XFEL source in a hot and dense plasma
C. Mossé, A. Calisti, S. Ferri, P. Genesio, O. Peyrusse and B. Talin 7

HEDP.I2: Measurements of plasma spectra from hot, dense elements and mixtures at conditions relevant to the solar radiative zone
D. J. Hoarty, P. Allan, S. F. James, C. R. D. Brown, L. M. R. Hobbs, M. P. Hill, J. W. O Harris, J. Morton, R. Shepherd, P. Beiersdorfer, H. Chen, E. Von Marley, J. Emig and E. Magee 9

HEDP.I3: Opacity Measurements and Analysis at Stellar Interior Conditions
G. A. Rochau, J. E. Bailey, T. Nagayama, G. P. Loisel, C. Blancard, J. Colgan, Ph. Cossé, G. Faussurier, C. J. Fontes, F. Gilleron, I. Golovkin, S. B. Hansen, C. A. Iglesias, D. P. Kilcrease, J. J. MacFarlane, R. C. Mancini, S. N. Nahar, C. Orban, J.-C. Pain, A. K. Pradhan, M. Sherrill and B. G. Wilson 10

MAGNETIZED PLASMAS **11**

MAG.I1: Atomic collision kinetics and dynamics in fusion edge plasmas: detailed book-keeping by integrated computations
D. Reiter 11

MAG.I2: Turbulence and atomic physics in magnetically confined plasmas
Y. Marandet, H. Bufferand, L. Carbajal-Gomez, G. Ciraolo, N. Nace, E. Serre, P. Tamain and M. Valentinuzzi 13

MAG.I3: Near infra-red spectroscopy of tokamak divertor plasmas
V. Soukhanovskii, A. G. McLean, S. L. Allen, and NSTX and DIII-D Research Teams 14

MAG.O1: Modeling of Stark-Zeeman line shapes in magnetic fusion plasmas
J. Rosato, L. Godbert-Mouret, M. Koubiti, Y. Marandet and R. Stamm 15

MAG.O2: Magnetic field effect in radiative recombination of bare uranium ions with electrons
D. Banaś, A. Gumberidze, P. Jagodziński, M. Pajek and Th. Stöhlker 16

ASTROPHYSICAL AND ATMOSPHERIC PLASMAS **17**

AAP.I1: Spectral modeling of astrophysical interest
C. J. Fontes 17

AAP.O1: A new generation of Los Alamos Opacity Tables
J. Colgan, D. P. Kilcrease, N. H. Magee, Jr, J. Abdallah, Jr., M. E. Sherrill, C. J. Fontes, P. Hakel, J. A. Guzik, K. A. Mussack and P. Walczak 19

AAP.I2: Astrophysical plasma modeling in the astro-H era
J. Kaastra 20

AAP.O2: Non-perturbative theory of radiative scattering, in the weak radiation field limit
V. Bommier 21

AAP.O3: Magnetic-field induced transitions: a novel method to determine magnetic fields in low-density plasmas
W. Li, J. Grumer, T. Brage, R. Hutton and Y. Zou 22

X-RAY SOURCES. I **23**

XRS.I1: Source development for extreme ultraviolet lithography and water window imaging
G. O'Sullivan, P. Dunne, D. Kilbane, B. Li, R. Lokasani, E. Long, F. O'Reilly, J. Sheil, E. Sokell, C. Suzuki, T. Wu and T. Higashiguchi 23

XRS.O1: Near-field and far-field structure of a seeded plasma-based soft x-ray laser
O. Guilbaud, O. Delmas, A. Le Marec, S. Kazamias, M. Pittman, B. Lucas, E. Baynard, J. Demailly, G. V. Cojocaru , R. G. Ungureanu , R. A. Banici , D. Ursescu , A. Klisnick and D. Ros 25

XRS.O2: Laser-produced plasma EUV source based on liquid tin droplets
D. Kurilovich, F. Torretti, J. Scheers, W. Ubachs, R. A. Hoekstra and O. O. Versolato 26

LOW TEMPERATURE PLASMAS. I **27**

LTP.I1: Plasma chemistry and kinetics in low pressure discharges: The significance of metastable states
J. T. Gudmundsson 27

LTP.I2: Picosecond two-photon absorption laser induced fluorescence for measuring reactive atomic species in atmospheric-pressure plasma jets
A. West, J. Bredin, S. Schrter, K. Niemi, J. Dedrick, D. OConnell, T. Gans and E. Wagenaars 29

LTP.O1: Heating and compression of laser produced plasma in a pulsed magnetic field
J. Creel, T. Donnelly and J. G. Lunney 30

LTP.O2: Iodine chemistry in global model and experiments
P. Grondein, T. Lafleur, P. Chabert and A. Aanesland 31

LTP.O3: Low temperature photoionized plasmas driven by LPP EUV sources
A. Bartnik, P. Wachulak, H. Fiedorowicz, W. Skrzeczanowski, R. Jarocki, T. Fok and L. Wegrzyński 32

WARM DENSE MATTER. I **33**

WDM.I1: X-ray spectroscopic studies of solid-density plasmas created by an X-ray free electron laser
J. S. Wark 33

WDM.I2: Free-electron x-ray laser measurements in isochorically heated warm dense matter
P. Sperling, H.-K. Chung, L. B. Fletcher, E. Galtier, E. J. Gamboa, H. J. Lee, H. Reinholz, G. Röpke, B. B. L. Witte, R. Redmer, U. Zastrau and S. H. Glenzer 35

WDM.O1: Generalized atomic processes for WDM: XFEL interaction with solids
F. Rosmej, B. Deschaud and O. Peyrusse 36

X-RAY SOURCES. II **37**

XRS.I2: Advances in non-equilibrium atomic physics with novel laser targets
J. D. Colvin, F. Perez, M. J. May, K. B. Fournier, S. Charnvanichborikarn, S. Kucheyev, E. Burks, K. Liu and T. E. Felter 37

XRS.I3: Toward ultrafast and polarization controllable plasma-based soft X-ray lasers
S. Sebban, A. Depresseux, E. Oliva, J. Gautier, F. Tissandier, J. Nejdl, M. Kozlova, G. Maynard, J. P. Goddet, A. Tafzi, A. Lifschitz, H. T. Kim, S. Jacquemot, V. Malka, K. Ta Phuoc, C. Thaury, P. Rousseau, G. Iaquaniello, T. Lefrou, A. Flacco, B. Vodungbo, G. Lambert, P. Zeitoun and A. Rousse 39

XRS.O3: Influence of partial temporal coherence on the spectral characterization of xuv laser pulses
A. Le Marec, P. Chavel, O. Guilbaud, O. Larroche and A. Klisnick 40

XRS.O4: Tunable EUV radiation source for laboratory based photoemission spectro- microscopy
D. Wilson, C. Schmitz, D. Rudolf, Sally Rieß, M. Schuck, C. Wiemann, A. Besmehn, H. Hardtdegen, C. M. Schneider, F. Stefan Tautz and L. Juschkin 41

XRS.O5: X-ray emission generated by laser-produced plasma from dielectric nanostructured targets
Z. Samsonova, S. Höfer , A. Hoffmann, B. Landgraf, M. Zürch, I. Uschmann, D. Khaghani, O. Rosmej, P. Neumayer, R. Röder, L. Trefflich, C. Ronning, E. Förster, C. Spielmann and D. Kartashov 42

LOW TEMPERATURE PLASMAS. II **43**

LTP.I3: State-to-state modeling of non equilibrium low temperature atomic plasmas
A. Bultel, V. Morel, J. Annaloro and M.-C. Druguet 43

LTP.O4: Ab-initio methods for core level spectra simulation of hydride molecular ions
A. Puglisi, N. Sisourat and S. Carniato 45

LTP.O5: Emission of fast non-Maxwellian hydrogen atoms in low-density laboratory plasmas
C. Brandt, O. Marchuk, A. Pospieszczyk and S. O. Dickheuer 46

A TRIBUTE TO CLAIRE AND JACQUES BAUCHE **47**

CJB.I1: A Survey on Interpreting Atomic Spectra in the Vicinity of Claire and Jacques Bauche
J.-F. Wyart 47

CJB.I2: Statistical properties of levels and lines in complex atomic spectra
J.-C. Pain and F. Gilleron 49

CJB.I3: Some remarks on global methods for the modeling of atomic physics in hot plasmas
O. Peyrusse 50

CJB.I4: Transition Arrays: Unresolved or Resolved
M. Klapisch 51

CJB.I5: Beyond the UTA approximation
C. A. Iglesias 52

ATOMIC DATA AND PROCESSES. II **53**

ADP.I3: Can quantum chaos prevent nuclear fusion?
G. F. Gribakin 53

ADP.O4: The Tungsten Project: Dielectronic Recombination data for Collisional-Radiative Modelling in ITER — W^{44+}-W^{74+}
S. P. Preval, N. R. Badnelland M. O'Mullane 55

ADP.I4: Status of QED tests in high-Z few electron ions
P. Indelicato 56

HIGH ENERGY DENSITY PLASMAS. II **57**

HEDP.I4: X-ray spectroscopy of inertial confinement fusion plasmas
R. C. Mancini 57

HEDP.I5: Non-LTE Modeling of Radiatively-Driven Dense Plasmas
H. Scott 59

HEDP.O1: PC Spectra analysis of L-shell copper X-pinch plasma produced by the compact generator of Ecole Polytechnique
M. F. Yilmaz, Y. Danisman, J. Larour and L. E Aranchuk 60

HEDP.O2: Simultaneous X and XUV opacity measurements in dense plasmas
M. Dozières, F. Thais, S. Bastiani-Ceccotti, T. Blenski, F. Gilleron, J.-C. Pain, M. Poirier, C. Reverdin, F. Rosmej, F. Condamine, V. Silvert, G. Soullié and B. Villette 61

HEDP.O3: M-shell resolved high-resolution X-ray spectroscopic study of transient matter evolution driven by hot electrons in kJ-laser produced plasmas
F. P. Condamine, M. Šmid, O. Renner, M. Dozières, F. Thais, P. Angelo and F. B. Rosmej 62

WARM DENSE MATTER. II **63**

WDM.O2: Classical molecular dynamics for non equilibrium correlated plasmas
A. Calisti, S. Ferri and B. Talin 63

WDM.O3: Accurate and efficient neutral pseudo-atom model to predict warm dense matter properties
L. Harbour, M. W. C. Dharma-wardana, D. D. Klug and L. J. Lewis 65

WDM.O4: Efficient calculation of atomic rate coefficients in dense plasmas
V. Aslanyan and G. J. Tallents 66

ATOMIC DATA AND PROCESSES. III **67**

ADP.O5: The Stark-B database VAMC node
S. Sahal-Bréchot, M. S. Dimitrijević, N. Moreau and N. Ben Nessib 67

ADP.O6: Atomic data for transitions in S V
V. Stancalie, V. Pais and C. Iorga 69

POSTERS: ATOMIC DATA AND PROCESSES **70**

ADP.P1: Collisional radiative model to study organi LIBS plasma
Z. Bedrane 70

ADP.P2: Searching for dielectronic satellite lines associated with 3s→2p transitions in Fe XVII
P. Beiersdorfer, G. V. Brown and A. Laska 72

ADP.P3: Electron-impact excitation and recombination of molecular cations in cold plasmas: application to H2+, BeH+, CH+, CO+, N2+, and BF+
F. Colboc, J. Zs. Mezei, S. Niyonzima, S. Ilie, M. D. Epée Epée, D. A. Little, B. Pérès, V. Morel, N. Pop, K. Chakrabarti, O. Motapon, D. Benredjem, A. Bultel, K. Hassouni, J. Tennyson and I. F. Schneider 73

ADP.P4: Plasma effects on atomic data for the K-vacancy states of highly charged iron ions
J. Deprince, S. Fritzsche, T. Kallman, P. Palmeri and P. Quinet 74

ADP.P5: Renormalization shielding effects on the electron-impact ionization in dense plasmas
Y. D. Jung 75

ADP.P6: Higher-order contribution in the resonant recombination of electron-ion interaction
G. Y. Liang, C. Beilmann, H. G. Wei, J. R. Crespo López-Urrutia and G. Zhao 76

ADP.P7: Analysis of the VUV emission spectrum of the Er^{3+} ion (Er IV)
A. Meftah, S. Ait Mammar, C. Blaess, N. Champion, L. Tchang-Brillet and J.-F. Wyart 77

ADP.P8: Extended analysis of trebly ionized selenium: Se IV
H. Noman and A. Tauheed 78

ADP.P9: K-shell spectroscopy in hot plasmas: Stark effect, Breit interaction and QED corrections
J.-C. Pain, F. Gilleron, M. Comet and D. Gilles 79

ADP.P10: Plasma diagnostics with EUV spectra from highly charged ions of Yttrium
R. Silwal, J. M. Dreiling, J. D Gillaspy, E. Takacs and Yu. Ralchenko 80

ADP.P11: Electron-impact excitation and ionization calculations for tungsten and molybdenum ions
M. Turkington, C. P. Ballance, C. A. Ramsbottom and A. Hibbert 81

ADP.P12: EBIT spectroscopy of highly charged Tin ions for EUV source diagnostics
A. Windberger, F. Torretti, S. Dobrodey, W. Ubachs, R. A. Hoekstra, J. R. Crespo López-Urrutia and O. O. Versolato 82

POSTERS: LOW TEMPERATURE PLASMAS **83**

LTP.P1: A monitoring method of chamber wall conditions using outgassing in He plasma
J. Bang, H. Lee and T. Kang 83

LTP.P2: Investigation on the role of the blocking capacitor in single and dual CCRF discharge
R. Benallal, A.Boudghene Stambouli, S. M. Mesli and M.Habchi 85

LTP.P3: Argon metastable density in an atmospheric microplasma jet in interaction with a dielectric surface
Et. Es-Sebbar, K. Gazeli, G. Bauville, M. Fleury, O. Neveu, S. Pasquiers, V. Puech and J. Santos Sousa 86

LTP.P4: Measurement of axial ion flow profiles in a linear helicon plasma without explicit de-convolution of the measured line shapes
J. Green, O. Schmitz and G. Severn 87

LTP.P5: Metastable influence on the collisional-radiative kinetics of a He-Ne discharge
J.-S. Macé, G. Maynard, B. Letourneur and T. Minea 88

LTP.P6: CH_4-CO_2 reforming in surface-discharge reactor containing ZnO-CuO/Al_2O_3 catalysts. Influence of the ratio ZnO/CuO on products distribution
A. Rahmani and M. Nikravech 89

LTP.P7: Experimental and theoretical plasma emission spectra of atomic and molecular gases in the UV/VIS region excited by intense EUV pulses
I. Saber, A. Bartnik, H. Fiedorowicz and W. Skrzeczanowski 90

POSTERS: HIGH ENERGY DENSITY PLASMAS **91**

HEDP.P1: Analysis of X-ray spectra measured on the PHELIX laser facility
M. Comet, J.-C. Pain, F.Gilleron, D. Denis-Petit, V. Méot, P. Morel, G. Gosselin, F. Hannachi, F. Gobet, M. Tarisien and M. Versteegen 91

HEDP.P2: Time-resolved spectroscopy diagnosis and energy balance of implosion cores in Omega experiments driven by shaped laser pulses
R. Florido, R. C. Mancini, T. Nagayama, R. Tommasini, J. A. Delettrez and S. P. Regan 93

HEDP.P3: NLTE opacity calculations in ICF plasmas. C+Si mixtures
W. Jarrah and D. Benredjem 94

HEDP.P4: High Density Plasmas: When the Average Atom is not equivalent to the Average of Atoms
L. Upcraft 95

HEDP.P5: Self-consistent dynamic approaches for the calculation of photoabsorption in plasmas
C. Caizergues, T. Blenski and R. Piron 96

POSTERS: WARM DENSE MATTER **97**

WDM.P1: A Relativistic Green's Function Quantum Average Atom Model
N. M. Gill and C. E. Starrett 97

POSTERS: ASTROPHYSICAL AND ATMOSPHERIC PLASMAS **99**

AAP.P1: Dust acoustic dressed soliton in dusty plasma with suprathermal ions
R. Amour and M. Tribeche 99

AAP.P2: Nonlinear damping of dust acoustic waves in a charge varying electronegative dusty plasma
M. Benzekka and M. Tribeche 101

AAP.P3: Ionization and heating of a neon gascell photoionized plasma experiment at the Z facility
R. Mancini, T. E. Lockard, D. C. Mayes, G. P. Loisel, J. E. Bailey, G. A. Rochau, J. Abdallah, R. Heeter and D. Liedahl 102

POSTERS: MAGNETIZED PLASMAS **103**

MAG.P1: Develoment of a temperature diagnostic in fluorine-like aluminum emission in the EUV
J. K. Lepson and P. Beiersdorfer, R. Kaita, R. Majeski and D. Boyle 103

MAG.P2: Turbulence and Transport Barrier Relation with Poloidal Magnetic Field in Damavnd Tokamak
M. Moslehi-Fard, N. Alinejad and A. Sadighzadeh 105

MAG.P3: Stark broadening by relativistic electrons in magnetic fusion plasmas
J. Rosato, S. Pandya, R. Reichle, R. Barnsley, I. Hannachi, Y. Marandet and R. Stamm 106

POSTERS: X-RAY SOURCES **107**

XRS.P1: Investigation of bright 13 keV Kr K-shell X-ray yields at the National Ignition Facility
M. J. May, J. D. Colvin, G. E. Kemp, K. B. Fournier, H. Scott, M. Patel, M. A. Barrios and K. W. Widmann 107

LECTURES **109**

Spectral Lines in Plasmas
Yu. Ralchenko, NIST Gaithersburg 109

Population Kinetics Modeling for Plasma Spectroscopic Analysis
H. K. Chung, IAEA, Vienna 111

Spectral lineshape modeling state of art
A. Calisti, PIIM, Aix-Marseille Université 112

An introduction to the interaction of X-ray free electron laser radiation with matter
F. Rosmej, Université Pierre et Marie Curie 113

Astrophysical X-ray spectra
J. Kaastra, SRON, Utrecht 114

Can we nurse the fire ? The physics of magnetic fusion
D. Reiter, Institute for Energy and Climate Research, Jülich 115

Author Index **116**

ATOMIC DATA AND PROCESSES. I

ATOMIC DATA QUALITY AND NEEDS FOR COLLISIONAL-RADIATIVE MODELING

Yuri Ralchenko[1]

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Reliable calculation of plasma kinetic characteristics and emission and/or absorption spectra necessarily involves large sets of atomic data such as state energies, radiative and autoionization transition probabilities, and collisional cross sections or rate coefficients. The quality and coverage requirements for such data often depend on a particular problem as various plasmas may exhibit non-Maxwellian distributions, anisotropy effects, or be under strong fields that may modify atomic structure.

In this talk we will present an overview of the recent efforts on analysis of data quality requirements and data needs for collisional-radiative modeling of diverse plasmas. Particular examples will cover x-ray spectroscopy and motional Stark effect diagnostics for magnetic fusion plasmas, multi-electron charge exchange for astrophysical applications, and simulation of extreme ultraviolet spectra from electron beam ion traps (EBITs).

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Invited

ATOMIC PROCESSES IN X-RAY FREE ELECTRON PRODUCED PLASMAS

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Collisional-Radiative (CR) models employing super-configuration atomic levels have been successfully used for a wide range of plasma conditions where electron collisional processes are prevalent in plasmas [1]. Particularly, a generalized CR model using hydrogenic configurations, FLYCHK, has been available through NIST web site (http://nlte.nist.gov/FLY) to provide experimentalists fast and simple but reasonable predictions of atomic properties of plasmas. For a given plasma condition, it provides charge state distributions and spectroscopic properties, which have been extensively used for experimental design and data analysis. It has been applied to various plasma conditions relevant to long or short-pulse laser-produced plasmas, tokamak plasmas, or astrophysical plasmas.

With the development of X-ray free electron lasers (XFEL), a novel state of matter of highly transient and non-equilibrium plasmas has been created in the laboratory. As high intensity x-ray laser beams interact with a solid density target, electrons are ionized from inner-shell orbitals, and Auger electrons and photo electrons are generated. These electrons and XFEL photons create dense and finite temperature plasmas and corresponding plasma conditions strongly correlate with the XFEL conditions.

In order to include self-consistent time-dependent plasma conditions of XFEL driven plasmas, the FLYCHK code was extended to the atomic kinetics model SCFLY containing an extensive set of configurations needed for solid density plasmas [2]. The code accepts the time-dependent conditions of XFEL as input parameters, and computes time-dependent population distribution and ionization distribution self-consistently with electron temperature and density assuming an instantaneous equilibration. The methods and assumptions in the atomic kinetics model and applications to various experiments including XFEL experiments will be presented.

References

1. H.-K. Chung, M.H. Chen, W.L. Morgan, Yu. Ralchenko, and R.W. Lee, High Energy Density Physics, **1**, 3 (2005)
2. H.-K. Chung, M.H. Chen and R.W. Lee, High Energy Density Physics **3**, 57 (2007)

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Invited

Electron-impact excitation and photoionization cross-sections involving low ionization stages of Cobalt for astrophysical plasmas

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Important Fe-peak species are often observed in astrophysical objects such as supernovae (SNe) [1] and cool stars [2]. Due to these important applications, we focus our attention towards the near neutral Co II and Co III systems. Accurate atomic data is therefore essential for many processes and transitions in order to carry out comparisons with observation. Infrared transitions observed in multiple SNe are considered to be useful temperature and density diagnostics [3], and also monitoring the time evolution of the photosphere and mass of synthesized Nickel [4].

The atomic wavefunctions for Co III were generated using the computer package GRASP0 [5] which includes the relativistic Hamiltonian operators. Spectroscopic orbitals up to 4p were optimized on various energy states of Co III, and a total of 262 levels were included in the close-coupling expansion that arise from the important configurations $3d^7$, $3d^6[4s, 4p]$ and the double electron promotions $3s^2 3p^4 3d^9$ and $3p^6 3d^9$ are included as configuration interaction terms. These wavefunctions were then used consistently in the R-matrix framework when considering electron and photon interactions.

The electron-impact excitation and single photon ionization were calculated using the Dirac Atomic R-matrix Codes (DARC) [6]. We will present total photoionization cross-sections from the ground and excited states, as well as level to level contributions. The latter are necessary for the calculation of the reverse radiative recombination process. For the electron impact excitation calculations we present results in the form of the effective collision strength, $\Upsilon_{i\to j}$.

References

1. C. L. Gerardy & W. P. S. Meikle et al., ApJ **661**, 995 (2007).
2. M. Bergemann & J. C. Pickering et al., MNRAS **401**, 1334 (2010).
3. P. Ruiz-Lapuente, Astron. Soc. of the Pacific Conf. Ser. **78**, 291 (1995).
4. C. M. Telesco & P. Höflich et al., ApJ **798**, 93 (2015).
5. F. A. Parpia & C. F. Fischer et al., Comp. Phys. Commun. **94**, 249 (1996).
6. P. G. Burke, R-matrix Theory of Atomic Collisions (2011).

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SPECTROSCOPY OF HIGHLY CHARGED IRON IONS RELEVANT TO ASTROPHYSICAL PLASMAS

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Spectroscopy is the most common technique used to investigate the ionization balance of astrophysical and laboratory plasmas. The emissions from highly charged ions (HCIs) are regularly observed in stellar objects such as solar corona, AGNs, stellar flares, supernova remnants etc. Fundamental to the understanding of heating, radiation mechanisms, ion abundances, ionization balance in all of these astrophysical objects depends on the availability of reliable diagnostics of electron density, temperature and lines identification. In the coronal temperature range (1−3 MK), Fe ions are considered to be the main source of density sensitive lines. These originate mainly below 300 Å, the wavelength region well covered with the EUV Imaging Spectromer (EIS) on board the Hinode satellite.

In this paper, we will describe our recent efforts to derive spectroscopic data of highly charged iron for astrophysical applications. We present high-resolution density sensitive intensity ratio measurements for Fe X-XII ions in EUV spectral wavelength below 300 Å. The present measurements were performed using a compact electron beam ion trap called CoBIT developed at the University of Electro-communications, Tokyo Japan [1, 2]. The EUV emission from the trapped ions was recorded with a flat-field grazing incidence spectrometer installed on CoBIT [3]. The derived intensity ratios for several density sensitive lines of Fe X-XII will be presented and compared with the calculations and with the data extracted from the EIS on board the Hinode satellite.

References

[1] Nakamura N, Watanabe E, Sakaue H A, Kato D, Murakami I, Yamamoto N, Hara H and Watanabe T 2011The Astrophysical Journal 739 17
[2] Nakamura, N., Kikuchi, H., Sakaue, H. A., & Watanabe, T. 2008, Rev. Sci. Instrum., 79, 063104
[3] Sakaue, H. A., Kato, D., Nakamura, N., et al. 2009, J. Phys.: Conf. Ser., 163, 012020

Atomic data and spectral models for low ionization Fe-peak ions

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We present extensive calculations of photoionization cross sections, radiative transition rates, electron impact collision strengths for neutral, singly, and doubly ionized Fe-peak ions. Computations of radiative data are carried out with a combination of multiconfiguration approaches, namely the relativistic Hartree–Fock, Thomas–Fermi–Dirac potential, and Dirac–Fock methods; while the R-matrix plus intermediate coupling frame transformation, Breit–Pauli R-matrix and Dirac R-matrix packages are used to obtain collision strengths. We examine the advantages and shortcomings of each of these methods, and estimate rate uncertainties from the resulting data dispersion.

We construct excitation balance spectral models, and compare the predictions from each data set with observed spectra from various astronomical objects. We are able to establish benchmarks in the modeling of observed astronomical spectra in the IR, optical and UV regions. Our spectral models include a detailed treatment of propagation of atomic data uncertainties.

Finally, we provide diagnostic line ratios and line emissivities for emission spectroscopy as well as column densities for absorption spectroscopy. All atomic data and models are available online and through the AtomPy atomic data curation environment.

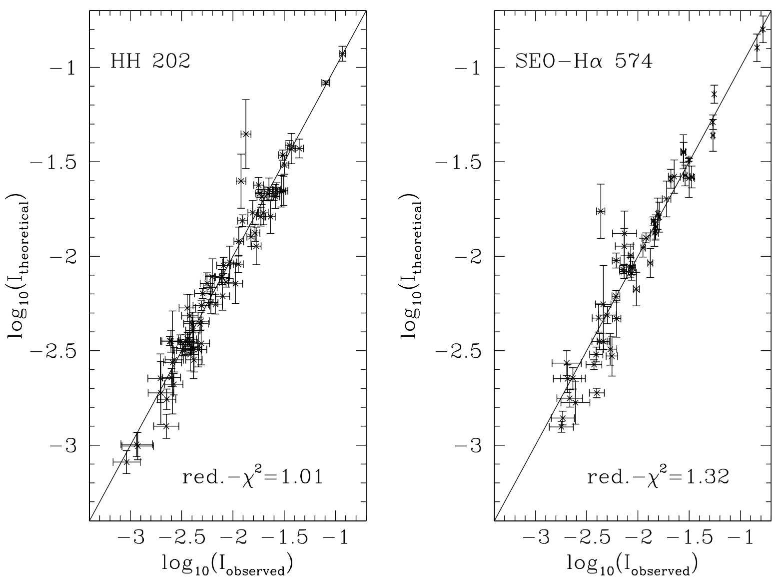

Figure 1: Comparison between observed and predicted [Fe II] line strengths for two different astronomical nebulae.

HIGH ENERGY DENSITY PLASMAS. I

PROSPECT OF PHOTO-PUMPING EXPERIMENT WITH XFEL SOURCE IN A HOT AND DENSE PLASMA

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The fourth generation light sources based on the X-ray free electron laser (XFEL) opens new perspectives in the investigation of high-energy-density plasmas. The properties of these tunable X-ray laser sources permit to consider an active spectroscopy experiments to improve the understanding of hot and dense plasmas.

The objective of such experiments is to create a plasma and then, to use the XFEL for pumping selectively individual transitions creating enhanced population in the excited states. The fluorescence emission can then be easily monitored for the validation and the improvement of the models. The idea has been used in studying lower density plasmas with visible lasers and can, with the XFEL, be employed in the context of high-density plasmas. Selectively pumping of the wings of a line transition and observing the radiative redistribution within the line profile will provide a tool for understanding the population kinetics, the radiative transfer and the underlying fundamental line shape broadening processes linked to the dynamics of the plasma (ionic field fluctuations, inelastic collisions, etc.), by comparison with theoretical models. This prospect of photo-pumping experiments is then a strong motivation as far on the experimental aspect as on the theoretical one, which implies hydrodynamics, population kinetics, atomic physics and spectral line shape studies.

In this work, we present prospective calculations of spectral line shapes and redistribution functions of the neon-like aluminum $1s2s^22p^6nl$-$1s^22s^22p^5nl$ (n=3,4,5,..) and $1s2s^22p^63l$-$1s^22s^22p^6$ lines at 1490eV and 1572 eV, respectively, for typical laser-plasma conditions. These calculations are based on a theoretical model for calculating the redistribution function in hot and dense plasmas [1]. It relies on an extension of the Frequency Fluctuation of Model [2]. This model takes into account the complexity of the atomic structure of ionic emitters and the various line broadening mechanisms including effects of the emitter environment fluctuations.

References

1. C. Mossé *et al.*, Phys. Rev. A **60**, 1005 (1999).
2. A. Calisti *et al*., Phys Rev. E **81**, 016406 (2010).

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ELEMENTS AND MIXTURES AT CONDITIONS RELEVANT TO THE MEASUREMENTS OF PLASMA SPECTRA FROM HOT, DENSE SOLAR RADIATIVE ZONE.

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Recent experiments using the Orion laser in the UK have pushed temperatures and densities produced in short pulse laser driven spectroscopic experiments to new highs with electron temperatures of up to 2.5keV and electron densities up to around $4x10^{24}$/cc. Emission spectra from plasmas at temperatures in the range of 500eV- 2.5keV have been studied by careful control of the laser irradiance and the target design. The use of dot samples buried in plastic or diamond combined with long pulse compression and short pulse heating has allowed the plasma density as well as the temperature to be changed systematically.

These techniques have been applied to study dense plasma effects such as ionization potential depression; line shapes in low Z elements and mixtures; the study of L shell emissivity from medium Z materials and electron transport in short pulse laser/solid target interaction. These results are presented along with the measurements of the plasma temporal behaviour using picosecond-timescale X-ray streak cameras and plasma radial gradients using time-resolving and time-integrating diagnostics to better understand the experimental errors. These plasma conditions are relevant to the study of the opacity of the solar interior and plans to extend the techniques to higher density closer to those at the solar core are discussed.

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Opacity Measurements and Analysis at Stellar Interior Conditions

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The opacity of matter is critical for understanding the dynamics of systems where radiation plays a significant role in the energy transfer such as stars, inertial confinement fusion, and many high energy density laboratory experiments. The broad range of elements and plasma conditions of importance for these systems dictates that we must rely on opacity model calculations, now and for the foreseeable future. However, detailed opacity calculations are enormously complex, and even low probability electron configurations and transitions are critical to accurately account for the bulk opacity. This therefore requires precise measurements of the frequency-dependent opacity across a range of materials and plasma conditions to test the physical underpinnings of the models, so they can be employed in a broad variety of regimes with high confidence. Precise laboratory opacity measurements have been limited in the past by the challenges of creating and diagnosing sufficiently large and uniform samples, particularly at the high temperature and density conditions found inside stars. We use the opacity science platform at the Sandia Z facility to measure wavelength-resolved opacity at electron temperatures Te = 156-195 eV and densities ne = 0.7 – 4.0E22 cm^-3, conditions very similar to the radiation/convection boundary region within the sun. The measured wavelength-dependent opacity of iron in the 975–1775 eV photon energy range is found to be 30-400% higher than predictions, with significant differences in the shapes and intensities of the L-shell spectral lines [1]. This data raises questions about how well we understand the behavior of atoms embedded in high energy density plasma. This talk will provide an overview of the measurements, the numerous investigations of possible errors, and ongoing experiments and simulations aimed at testing hypotheses for the model-data discrepancy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

References

[1] J.E. Bailey et al. A higher-than-predicted measurement of iron opacity at solar interior temperatures. Nature 517, 56 (2015).

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MAGNETIZED PLASMAS

ATOMIC COLLISION KINETICS AND DYNAMICS IN FUSION EDGE PLASMAS: DETAILED BOOK-KEEPING BY INTEGRATED COMPUTATIONS

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Magnetic fusion edge plasma transport models, used, e.g., during the design and preparation phases of ITER, resort to a large number of atomic (A) , molecular (M) and plasma-material interaction PMI data, in order to quantify the related processes in the context of the complex plasma flows in the outer and near surface region of the fusion plasma. Many different computational edge plasma models are in use, but common to most of them is a 2D or 3D fluid (CFD) treatment of the main plasma (electrons, ions) components, and a microscopic (kinetic, often "Monte Carlo" treatment of the atomic, molecular and some low concentration impurity ions. The B2-EIRENE family of codes [1] is such a widely used example. It builds, for example, the plasma transport part also of the SOLPS suit of codes, notably the SOLPS_ITER code hosted by ITER-IO.

These primary computational tools, which take A+M data as input, have to deal with the highly complex 'plasma state of matter' issues first. They are far less mature and limited in their predictive quality than computational tools in other areas of sciences, e.g. than those taking nuclear data as input.

The data challenge (A+M+PMI data) in codes such as B2-EIRENE (see: www.eirene.de) often comes in at a peripheral level, dealing with albeit important, sometimes decisive, sub-components of the model. Computational fusion plasma science, at least with so called integrated models covering many individual effects in a single model, can be regarded as an attempt to separate, computationally, known from unknown. This is needed in order to isolate the latter sub-components and make them accessible for experimental quantification. If this separation is made, then, quite distinct from other applications of atomic processes in plasmas, here the A+M data fall into the category 'known', whereas plasma turbulence, PMI and flows and all its consequences fall into the category 'unknown'.

In the present contribution we publicly expose the status of atomic, molecular and PMI data in fusion edge plasma codes, and we discuss their journey from the raw, unprocessed data towards condensed, properly averaged data used in computational models, as well as first attempts to quantify the uncertainty propagation during this data processing step. This latter is achieved by a (linear) sensitivity analysis option build into collision radiative codes for fusion plasma transport applications (as available under: www.hydkin.de) .

References

1. D. Reiter et al., Fusion Science and Technology, **47**, 172 (2005).

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TURBULENCE AND ATOMIC PHYSICS IN MAGNETICALLY CONFINED PLASMAS

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Atomic Physics processes play a key role in magnetically confined fusion (MCF) plasmas. Interactions between electrons and fuel ions (D^+, T^+ ions) with non-fully striped species (D and T atoms, and impurities such as W and Be in ITER) provide particle, momentum and energy sources/sinks for the fuel plasma, as well as means to diagnose (i.e. measure indirectly) physical parameters like plasma density and temperature. This contribution focuses on the peripheral regions of tokamaks, close to the material walls, where turbulence with order unity fluctuations is known to exist. These peripheral regions play an essential role in MCF plasmas, namely they have to exhaust fusion power in a way that is tolerable for plasma facing components. Current modelling of these issues rely on mean field models for charged species and the neutral gas, in which turbulent fluctuations are averaged out and the result transport is modelled by a simple closure. We show that this mean field description introduces additional difficulties in the description of atomic processes, in part because rate coefficients are non-linear function especially of the temperature. By looking at the transport of neutral atoms in a turbulent plasma background, we show that even neglecting these non-linearities lead to potentially marked effects, especially for molecules and impurity atoms sputtered from the wall [1]. We show that introducing "fluctuation dressed" rate coefficients could allow one to capture these effects in mean field descriptions of the plasma. The more general case of the ionisation balance of impurities in presence of fluctuations is considered next, showing that temperature fluctuations can affect the mean ionisation balance because of enhanced ionisation [2]. The last part of the contribution deals with optical diagnostics of fluctuations, applying the results obtained on the transport of atoms in fluctuating background to Gas Puff Imaging (GPI) and Beam Emission Spectroscopy (BES) fluctuations measurements. GPI and BES are related diagnostic techniques, for which atoms are injected into the plasma to provide line emission through electron collision excitation. The analysis of the experimental data requires careful assessment of the relationship between the quantity measured (light intensity integrated along the view of the camera) and the 3D distribution of plasma parameters (density, temperature). The so-called Shadowing effects are discussed in both contexts [3,4], as well as interpretation pitfalls with the often used 587.6 nm Helium I line, for which the effects of density and temperature fluctuations can compensate each other [4].

[1] A. Mekkaoui, Y. Marandet et al., Phys. Plasmas **19** 122310 (2012).

[2] F. Guzman, Y. Marandet et al., Plasma Phys. Control. Fusion **57** 125014 (2015).

[3] D. Moulton, Y. Marandet et al., Nuclear Fusion **55** 073025 (2015).

[4] D. Moulton, Y. Marandet et al., Contrib. Plasma Phys. **54** 575, (2014).

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ELEMENTS AND MIXTURES AT CONDITIONS RELEVANT TO THE MEASUREMENTS OF PLASMA SPECTRA FROM HOT, DENSE SOLAR RADIATIVE ZONE.

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Recent experiments using the Orion laser in the UK have pushed temperatures and densities produced in short pulse laser driven spectroscopic experiments to new highs with electron temperatures of up to 2.5keV and electron densities up to around $4x10^{24}$/cc. Emission spectra from plasmas at temperatures in the range of 500eV- 2.5keV have been studied by careful control of the laser irradiance and the target design. The use of dot samples buried in plastic or diamond combined with long pulse compression and short pulse heating has allowed the plasma density as well as the temperature to be changed systematically.

These techniques have been applied to study dense plasma effects such as ionization potential depression; line shapes in low Z elements and mixtures; the study of L shell emissivity from medium Z materials and electron transport in short pulse laser/solid target interaction. These results are presented along with the measurements of the plasma temporal behaviour using picosecond-timescale X-ray streak cameras and plasma radial gradients using time-resolving and time-integrating diagnostics to better understand the experimental errors. These plasma conditions are relevant to the study of the opacity of the solar interior and plans to extend the techniques to higher density closer to those at the solar core are discussed.

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MODELING OF STARK-ZEEMAN LINE SHAPES IN MAGNETIC FUSION PLASMAS

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We report on recent investigations of Stark-Zeeman hydrogen line shapes in magnetic fusion plasmas. In specific scenarios, tokamak edge and divertor plasmas involve an electron density sufficiently high (up to a few 10^{15} cm^{-3}) and a temperature sufficiently low (down to $T_e < 1$ eV) so that the hydrogen isotope lines routinely measured for diagnostic purposes are affected by Stark broadening and can be used as a probe of the electron density. An analysis of lines with a low principal quantum number such as Dα requires a careful treatment because the Stark broadening can be of the same order as the Doppler broadening and it can be affected by ion dynamics. Furthermore, the presence of a strong magnetic field (of the order of several teslas) results in an alteration of the energy level structure, which is not straightforward even for hydrogen due to the simultaneous action of the magnetic field and the plasma's microscopic electric field. In this work, we present models and discuss their applicability to the diagnostic of large scale devices such as ITER and DEMO. The influence of line reabsorption on the interpretation of spectra is also discussed.

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MAGNETIC FIELD EFFECT IN RADIATIVE RECOMBINATION OF BARE URANIUM IONS WITH ELECTRONS

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The influence of magnetic field on radiative recombination (RR) of bare ions with cooling electrons, which was observed in experiments in ion storage/cooler rings [1-3] have attracted a wide interest to interpret this observation [4, 5]. As it was found experimentally the measured RR rates for very low electron-ion energies exceed the standard quantum mechanical predictions, which, on the other hand, agree with experiments for higher relative energies. This, so called, enhancement effect was studied in more details experimentally in Ref. [1], where the scaling of excess of RR rates on the magnetic guiding field in the electron cooler and the electron beam temperatures, characterizing a flattened distribution of electron velocities, was established. However, the existing interpretations [4, 5] of the enhancement effect still do not fully explain the observations.

In order to investigate the effect of magnetic field on RR in more details, the state-selective x-ray RR experiment has been performed in the electron cooler of the ESR storage ring with decelerated bare U^{92+} ions recombining with electrons for relative electron-ion energies in the range 0-1000 meV [6] . In this experiment the x-ray K-RR photons emitted from radiative recombination into the K- and L-shells were measured in coincidence with recombined U^{91+} ions. By comparing the measured RR rate coefficients with fully relativistic RR calculations, which reproduce the data for higher relative electron-ion energies quite well, the enhancement of RR for the lowest n=1 and n=2 states was derived for the cooling condition, i.e. the zero average relative energy. This result is a strong argument against interpretation of the RR enhancement as a results of recombination into high Rydberg states followed by decay of these intermediate states.

In this paper we discuss the observed enhancement of RR as a result of the guiding magnetic field in the electron cooler, which affects the electron trajectories. First, we present a simplified model of radiative recombination in strongly magnetized cold plasma, which explains the main features of the observed RR enhancement, including the scaling with magnetic field and electron beam temperatures. Second, the effect of the magnetic field was studied in a more detailed manner by performing the Monte Carlo simulations of RR for helical electron trajectories. The importance of this interpretation of the observed enhancement effect will be discussed here in details in a context of the RR experiment for bare uranium ions interacting with cooling electrons.

References

1. G. Gwinner et al., Phys. Rev. Lett. **84**, 4822 (2000).
2. A. Hoffknecht et al., Phys. Rev. **A63**, 012702 (2000).
3. W. Shi et al., Eur. Phys. J. **D15**, 145 (2001).
4. C. Heerlein et al., Phys. Rev. Lett. **89**, 083202 (2002).
5. M. Hörndl et al., Phys. Rev. Lett. **95**, 243201 (2005).
6. D. Banaś et al., Phys. Rev. **A92,** 032710 (2015).

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ASTROPHYSICAL AND ATMOSPHERIC PLASMAS

SPECTRAL MODELING OF ASTROPHYSICAL INTEREST

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The Los Alamos suite of atomic physics and plasma modeling codes [1] can be used to generate large data sets and to model plasmas over a broad range of conditions. Recent applications include x-ray diagnostics of inertial confinement fusion experiments [2], spectral modeling of tungsten for magnetic fusion research [3], laser induced breakdown spectroscopy [4], non-LTE modeling of dynamic hohlraum driven experiments [5], and the large-scale generation of LTE opacities for the first thirty elements of the periodic table for the Los Alamos OPLIB database [6,7]. The suite has been recently used to model the spectral properties of diverse astrophysical plasmas, such as supernova remnants [8] and neutron star mergers [9]. In this work, an update is provided concerning the modeling of astrophysical plasmas of interest.

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References

1. C.J. Fontes, H.L. Zhang, J. Abdallah, Jr., R.E.H. Clark, D.P. Kilcrease, J. Colgan, R.T. Cunningham, P. Hakel, N.H. Magee and M.E. Sherrill, J. Phys. B **48**, 144014 (2015).
2. P. Hakel, G.A. Kyrala, P.A. Bradley, N.S. Krasheninnikova, T.J. Murphy, M.J. Schmitt, I.L. Tregillis, R.J. Kanzleieter, S.H. Batha, C.J. Fontes, M.E. Sherrill, D.P. Kilcrease and S.P. Regan, Phys. Plasmas **21**, 063306 (2014).
3. J. Colgan, C.J. Fontes, H.L. Zhang and J. Abdallah, Jr., Atoms **3**, 76 (2015).
4. H.M. Johns, D.P. Kilcrease, J. Colgan, E.J. Judge, J.E. Barefield II, R.C. Wiens and S.M. Clegg, J. Phys. B **48**, 224009 (2015).
5. M.E. Sherrill, J. Phys. B **48**, 224007 (2015).
6. J. Colgan et al, Ap. J, submitted (2015).
7. http://aphysics2.lanl.gov/opacity/lanl
8. C.J. Fontes, K.A. Eriksen, J. Colgan, H.L. Zhang and J.P. Hughes, High Energy Density Phys. **10** 43 (2014).
9. C.J. Fontes, C.L. Fryer, A.L. Hungerford, P. Hakel, J. Colgan, D.P. Kilcrease and M.E. Sherrill, High Energy Density Phys. **16**, 53 (2015).

A new generation of Los Alamos Opacity Tables

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(Dated: November 17, 2015)

Abstract

We report on a recently completed set of Los Alamos OPLIB opacity tables for the elements hydrogen through zinc [1]. Our tables have been computed using the Los Alamos ATOMIC code, which make use of atomic structure calculations that include fine-structure detail for all the elements considered. We utilize an equation-of-state model, known as ChemEOS [2], that is based on the minimization of free energy in a chemical picture. Recent publications by us [1,3] have compared our calculations to available experimental opacity data and to other opacity calculations. Our tables are publicly available via our website [4], and have already been used in solar modeling calculations [1,5] as well as the modeling of pulsations of B stars [6]. This presentation will give an overview of our opacity calculations and briefly review the conclusions from the astrophysical modeling. The Los Alamos National Laboratory is operated by Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under Contract No. DE-AC5206NA25396.

[1] J. Colgan et al, Ap. J, submitted (2015).

[2] P. Hakel, & D. P. Kilcrease, 14th Topical Conference on Atomic Processes in Plasmas, Eds: J. S. Cohen, S. Mazevet, and D. P. Kilcrease, (New York: AIP), pp 190 (2004).

[3] J. Colgan et al, Proceedings of the International Conference on Atomic and Molecular Data, pp 17 (2013); J. Colgan et al, High Energy Density Physics **9**, 369 (2013); J. Colgan et al, High Energy Density Physics, **14**, 33 (2015).

[4] http://aphysics2.lanl.gov/opacity/lanl

[5] J. A. Guzik, C. J. Fontes, P. Walczak, S. R. Wood, K. Mussack, and E. Farag, XXIXth IAU General Assembly Proceedings, August 2015 (Cambridge University Press, 2015).

[6] P. Walczak et al, A & A **580**, L9 (2015).

ASTROPHYSICAL PLASMA MODELING IN THE ASTRO-H ERA

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With the launch of the Japanese X-ray satellite ASTRO-H in February 2016, a new era for high-resolution X-ray spectroscopy of astrophysical plasmas will begin. For the first time high-resolution spectra of spatially extended sources can be obtained and the satellite has enhanced spectroscopic sensitivity around the Fe-K band at 6 keV. These new observational capabilities request improved spectroscopic codes to model these new data.

Building on a long tradition that started with Rolf Mewe in 1970, at SRON such spectroscopic tools have been developed. Motivated by the launch of ASTRO-H, we have significantly improved the code and extended it. It is publicly available as version 3.0 of the analysis package SPEX (www.sron.nl/spex).

In this presentation I give a few examples of these recent developments. We have prepared new parameterisations of radiative recombination rates, collisional ionisation and excitation rates that allow fast evaluation of the emerging spectra under various conditions, like ionising plasmas, photo-ionised plasmas and charge exchange processes. In particular in the latter case we have obtained already some spectacular results that will be shown in this presentation.

NON-PERTURBATIVE THEORY OF RADIATIVE SCATTERING, IN THE WEAK RADIATION FIELD LIMIT

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This work aims to the interpretation of the linear polarization spectrum observed close to the solar limb but on the disk, which forms the so-called "Second Solar Spectrum" [1]. The last is very different from the intensity spectrum, and therefore likely provides a different information, for instance on the magnetic field vector or on the medium anisotropy. The emitted radiation is essentially formed by scattering. Far wings due to partial redistribution are observed in 30% of the spectral lines [2].

It will be first shown that the second-order perturbation theory is unable to fully describe the frequency redistribution in the far wings. Since the Rayleigh/Raman scattering appears only at the fourth order, the development has to be pursued beyond the second order. It will be shown how this series development can be transformed into an infinite sum, which can then be evaluated at infinity [3], thus overcoming the Markov approximation.

In a second part, addressing the problem of the scattering by multilevel atoms, the different processes entering the redistribution will be discussed, which are namely the Rayleigh/Raman scattering and the coupling between the frequency coherence and the Doppler effect in the laboratory reference frame. These two processes are different, but they are shown to be weighted by part of the same collisions in the redistribution description. Consequences of this fact will be discussed, in terms of redistribution model. It will be shown that the statistical equilibrium equations have to be resolved for each atomic velocity class, leading to departures from the Maxwellian velocity distribution in the excited states [4].

References

1. J. O. Stenflo, Scattering Physics. *Solar Physics* **164**, 1-20 (1996).
2. L. Belluzzi, E. Landi Degl'Innocenti, A spectroscopic analysis of the most polarizing atomic lines of the second solar spectrum. *Astronomy and Astrophysics* **495**, 577-586 (2009).
3. V. Bommier, Master equation theory applied to the redistribution of polarized radiation, in the weak radiation field limit. I. Zero magnetic field case. *Astronomy and Astrophysics* **328**, 706-725 (1997).
4. V. Bommier, Master equation theory applied to the redistribution of polarized radiation, in the weak radiation field limit. III. Theory for the multilevel atom. *Astronomy and Astrophysics*, resubmitted (2016).

MAGNETIC-FIELD INDUCED TRANSITIONS: A NOVEL METHOD TO DETERMINE MAGNETIC FIELDS IN LOW-DENSITY PLASMA

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Magnetic fields play an important role in many different astrophysical and laboratory plasma, e.g. solar protuberances, tokamaks, ion traps and storage rings. They affect ions by introducing splitting of otherwise degenerated energy levels. An even more interesting effect is that the external field breaks the atomic symmetry and mixes states that have the same magnetic quantum number and parity. This will in turn introduce new decay channels from excited states, which we will label as magnetic-field induced transitions (MITs). These transitions have attracted new attention recently, due to the development of accurate and systematic methods of calculations for their rates [1,2,3] and the possible application as a tool for measuring plasma magnetic fields.

The problem is that the internal magnetic fields in the ions are strong and this effect is only observable for comparable magnetic field strength. However, sometimes MITs can be enhanced by a close, accidental degeneracy of two quantum states. It is fortunate that such a close degeneracy occurs for Fe X, since this ion has a high abundance in astrophysical plasmas including the solar corona. Since the determination of the magnetic fields in the solar corona still poses one of the major remaining challenges in solar physics, the MIT in Fe X is proposed as a new method for a continuous space based measurement of the coronal magnetic field.

We will give an overview of the recent progress in this field in general and in particular present our results or Fe X. An important parameter in determining the size of the effect an external magnetic field as on the MIT is the degree of pseudo-degeneracy between the levels involved. We have made a measurement of this energy separation in Fe X using an Electron Beam Ion Trap [4]. The measured value confirms that the splitting is small enough for the MIT-intensity to be sensitive to magnetic fields in the active solar corona range. Finally we propose a method for using Fe X line ratios to determine the coronal magnetic field strength [5].

References

1. J Li, J Grumer, W Li, M Andersson, T Brage, R Hutton, P Jönsson, Y Yang and Y Zou, Phys. Rev. A **88**, 013416 (2013).
2. J Grumer,W Li, D Bernhardt, J Li, S Schippers, T Brage, P Jönsson, R Hutton and Y Zou, Phys. Rev. A **88**, 022513 (2013).
3. W. Li, J. Grumer, Y. Yang, T. Brage, K. Yao, C. Chen, T. Watanabe, P. Jönsson, H. Lundstedt, R. Hutton and Y Zou, Astrophys. J. **807**, 69 (2015).
4. J Xiao, R Zhao, X Jin, B Tu, Y Yang, D Lu, R Hutton, and Y Zou, Proc. IPAC2013 MOPFI066, (2013).
5. W Li, Y Yang, B Tu, J Xiao, J Grumer, T Brage, T Watanabe, R Hutton and Y Zou, prepared for Phys. Rew. Lett.

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X-RAY SOURCES. I

SOURCE DEVELOPMENT FOR EXTREME ULTRAVIOLET LITHOGRAPHY AND WATER WINDOW IMAGING

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Sources for extreme ultraviolet lithography (EUVL) must be capable of producing hundreds of watts of extreme ultraviolet (EUV) radiation within a wavelength bandwidth of 2% centred on 13.5 nm, based on the availability of Mo/Si multilayer mirrors (MLMs) with a reflectivity of ~70% at this wavelength. Source development has focused on laser produced and discharge plasmas in order to identify which ions are the strongest emitters at this wavelength and the plasma conditions under which their emission can be optimized. It emerged that transitions of the type $4p^64d^n - 4p^54d^{n+1} + 4d^{n-1}4f$ which overlap in a narrow wavelength range in the spectra of Sn IX to Sn XIV were the best candidates but because of their opacity, especially in lower stages, radiation transport was a major challenge. In order to maximise plasma emission the density should be sufficiently low to minimise absorption but yet dense enough to maximise the coupling of laser radiation into EUV emission. The solution has been to irradiate tin droplets with a Nd:YAG pre-pulse which ionises the droplet and then reheat the resulting plasma with a CO_2 pulse when its density is close to the critical density for CO_2 radiation ~10^{19}cm^{-3} [1].

Subsequently development of other sources at 6.*X* nm, where $X \sim 0.7$, has been identified for so-called Beyond EUVL (BEUVL), based on the availability of La/B based MLMs, with theoretical reflectance approaching 80% at this wavelength. Laser produced plasmas of Gd have been identified as a potential source, as $n = 4 - n = 4$ transitions in Gd ions emit strongly near this wavelength. However to date, the highest conversion efficiency (CE) obtained, for laser to BEUV energy emitted within the 0.6% wavelength bandwidth of the available mirrors is only 0.8%, compared with values of 5% for the 2% bandwidth relevant for the Mo/Si mirrors at 13.5 nm [2]. This suggests a need to move to other sources, such as free electron lasers, for BEUVL.

Sources for other applications are being developed. Conventional sources for soft x-ray microscopy use H-like line emission from liquid nitrogen or carbon containing liquid jets which can be focused using zone plates. Recently the possibility of using MLMs with n=4-n=4 emission from a highly charged Bi plasma was proposed [3]. Subsequently, a number of promising alternative candidates have been found in spectra from LPPs of 2nd and 3rd transition row elements [4,5] whose emission coincides with the reflectance characteristics of available MLMs.

References:

[1] G O'Sullivan *et al.* J. Phys. B: At. Mol. Opt. Phys. **48** 144025 (2015)
[2] G. O'Sullivan *et al.*. Phys. Scr. **90** 054002. (2015)
[3] T. Higashiguchi *et al.* Appl. Phys. Letts. **100** 014103 (2012)
[4] B W Li *et al.* Appl. Phys. Letts, **102** 041117 (2013)
[5] T. Wu *et al.* J. Phys. B: At. Mol. Opt. Phys. **48** 245007. (2015)

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Invited

Near-field and far-field structure of a seeded plasma-based soft x-ray laser

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Plasma-based soft x-ray lasers are powerful sources of soft x-ray beams working in the range of 30 nm – 40 nm for plasma amplifiers generated from gaseous targets and 10 nm-20 nm for solid target laser-produced plasmas. A population inversion between excited levels of close-shell ions of the plasma leads to strong gain in a narrow soft x-ray spectral bandwidth and to amplification of spontaneous emission (ASE). The coherence and pulse duration is dramatically improved when a high order harmonic (HH) spectrally resonant with the laser transition is sent at the entrance of the plasma [1][2]. Besides, as the harmonic pulse is shorter than the dephasing and decaying time of the laser transition, coherent population transfer is theoretically predicted, leading to Rabi oscillation and very intense short soft x-ray pulses [3]. However, plasma non-uniformity and beam refraction into density gradient are expected to smear up these oscillations or lead to pi-pulse amplification regime [5]. It is therefore crucial to control the seeded beam propagation before any attempt to measure Rabi oscillation, and this task is even more difficult for solid target generated plasmas.

In the present communication, we will describe the ongoing experiments performed on the LASERIX facility aiming at controlling the beam parameters of a seeded laser at 32nm (Ne-like Ti)[5]. Large plasmas are produced from a Titanium solid target by a Nd-YAG auxiliary laser. The plasma is ionised up to the lasing ionisation stage, in a controlled range of density, with a hundred of millijoules picosecond laser pulse from a 30TW Ti:Sapphire laser system [6]. This pulse is followed 50ps latter by a 1J picosecond laser pulse that induce the population inversion through electron colisionnal pumping. A fourth laser pulse is recompressed to 30fs duration and focussed in a gas cell in order to generate the HH seed. Near field and far field images of the seeded beam have been recorded. Different patterns have been observed as a function of the injection delay: HH beam deflection, amplification, small scale fringes and beam splitting. These patterns have been reproduced numerically. They give valuable information on the plasma density gradient on a <100fs timescale.

References

[1] P. Zeitoun et al., Nature 431, 426 (2004)
[2] Y. Wang et al., Phys Rev Lett. 97, 123901 (2006)
[3] C.M. Kim et al., Phys. Rev. A 80, 053811 (2009)
[4] O. Larroche et al., Phys. Rev. A 88, 022815 (2013)
[5] O. Guilbaud et al. , Optics letters 40, 4775-8 (2015)
[6] R. A. Banici et al., Optics letters **37**, 51305132 (2012)

LASER-PRODUCED PLASMA EUV SOURCE BASED ON LIQUID TIN DROPLETS

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A low repetition rate (10 Hz) extreme-ultraviolet (EUV) light source was built and commissioned at ARCNL to study the fundamental physics aspects of its inner workings. It is based on a laser-produced plasma (LPP) generated by the irradiation of a high-energy infra-red pulse from an Nd:YAG laser onto a ~50 micron diameter tin droplet. We are currently setting up plasma diagnostic tools including those for imaging and spectroscopy at EUV and visible wavelengths, as well as ion detectors and shadowgraphy cameras which enable high-speed “movies” to be obtained from exploding droplets. In a recent study, the propulsion and shaping of a liquid indium-tin micro-droplet was experimentally investigated where we found that the droplet propulsion can be accurately described in terms of plasma pressure, and we provide a scaling law for the imparted momentum that enables the optimization of the laser-droplet coupling. These findings are of particular relevance to extreme ultra-violet (EUV) light sources.

LOW TEMPERATURE PLASMAS. I

PLASMA CHEMISTRY AND KINETICS IN LOW PRESSURE DISCHARGES: THE SIGNIFICANCE OF METASTABLE STATES

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The volume averaged global model is an approach to get a detailed description of the plasma chemistry in low pressure discharges. The main idea of a global model is to neglect the complexity which arises when spatial variations are considered and to generate a model that encompasses a large number of reactions in order to model a processing plasma with a limited computing power. The model allows us to explore the relative reaction rates for the creation and destruction of particular species over the pressure range of interest. Furthermore we can investigate various phenomena, such as the effects of metastable species, effects of the electron energy distribution function [1], negative ions and particular reactions on the overall discharge. Examples are taken from studies of oxygen [2,3], hydrogen [4] and chlorine [5,6] discharges. Then we discuss particle-in-cell Monte Carlo (PIC-MC) method which is a self-consistent kinetic approach capable of predicting the electron energy distribution function (EEDF) and ion energy distribution function (IEDF) for ions arriving at substrates. The object-oriented plasma device one (oopd1) code is a one-dimensional object-oriented PIC code. In 1d-3v PIC codes, such as oopd1, the model system has one spatial dimension and three velocity components. We explore a typical capacitively coupled chlorine [7] and oxygen [8,9,10] discharges and obtain key plasma parameters, including particle density, effective electron temperature, electron energy probability function and ion energy and angular distributions for both atomic ions and molecular ions. For molecular gas discharge we apply a hybrid approach where a volume averaged global model is used to determine the dissociation fraction which is then used in the PIC-MCC simulation. We discuss the dependence of the plasma parameters on the discharge pressure such as how the heating mechanism evolves from both stochastic and Ohmic heating to predominantly Ohmic heating and how the electron heating outweighs the ion heating at high pressure. We find that at higher pressures (> 30 mTorr) in an oxygen discharge, detachment by the metastable molecule $O_2(a^1\Delta_g)$ has a significant influence on the discharge properties such as the electronegativity, the effective electron temperature and the electron heating processes [9,10]. At a low pressure (10mTorr), Ohmic heating in the bulk plasma (the electronegative core) dominates, and detachment by $O_2(a^1\Delta_g)$ has only a small influence on the heating process. Thus at low pressure, the EEPF is convex and as the pressure is increased the number of low energy electrons increases and the number of higher energy electrons (> 10 eV) decreases, and the EEPF develops a concave shape or becomes bi-Maxwellian [10].

References

1. J. T. Gudmundsson, Plasma Sources Sci. Technol. **10** 76 (2001)
2. J. T. Gudmundsson and E. G. Thorsteinsson, Plasma Sources Sci. Technol. **16** 399 (2007)
3. D. A. Toneli *et al.*, J. Phys. D: Appl. Phys. **48** (2015) 325202
4. A. T. Hjartarson *et al.*, Plasma Sources Sci. Technol. **19** (2010) 065008
5. E. G. Thorsteinsson and J. T. Gudmundsson, Plasma Sources Sci. Technol. **19** (2010) 055008
6. E. G. Thorsteinsson and J. T. Gudmundsson, Plasma Sources Sci. Technol. **19** (2010) 015001
7. Shuo Huang and J. T. Gudmundsson, Plasma Sources Sci. Technol. **24** (2015) 015003
8. J. T. Gudmundsson *et al.*, Plasma Sources Sci. Technol. **22** (2013) 035011
9. J. T. Gudmundsson and M. A. Lieberman, Plasma Sources Sci. Technol. **24** (2015) 035016
10. J. T. Gudmundsson and B. Ventéjou, J. Appl. Phys. **118** (2015) 153302

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PICOSECOND TWO-PHOTON ABSORPTION LASER INDUCED FLUORESCENCE FOR MEASURING REACTIVE ATOMIC SPECIES IN ATMOSPHERIC-PRESSURE PLASMA JETS

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Atmospheric-pressure plasma jets (APPJs) are non-equilibrium, highly reactive plasmas that can operate at room temperature and in open air. This unique combination of characteristics makes them ideal tools for industry, replacing some traditional low-pressure methods, and healthcare. Emerging applications in plasma medicine include sterilisation of medical instruments, surgical tools for cutting and direct treatment of living cells in the human body. To guarantee effective and safe use of these devices in healthcare applications, it is vital to establish a thorough understanding of the physics and chemistry in APPJs. Many studies have suggested the importance of reactive oxygen and nitrogen species (RONS) such as O, N, H, $O_2^*(^1\Delta)$, O_3, OH, NO, H_2O_2, N_2O for medical treatments. It is known that APPJs produce large quantities of RONS, however, what mixture of RONS is created is largely unknown. The starting point for the creation of many of the different RONS is the production of atomic species, O, N and H. Unfortunately, measuring absolute densities of these species directly in an open-air environment is experimentally challenging.

Two-photon Absorption Laser-Induced Fluorescence (TALIF) spectroscopy is a well-known technique for measuring absolute, ground-state densities of atomic plasma species in low-pressure plasma applications. The biggest issue faced when applying this technique to atmospheric-pressure plasmas is the effect of collisional quenching, i.e. non-radiative decay of the laser-excited state. At low-pressure these quenching effects are minor, but at high pressure they become significant, reducing the excited state lifetime from tens or hundreds of nanoseconds (natural lifetime) to a few ns or less. Correcting for these quenching effects is sometimes possible if the life time is reasonably long compared to the laser pulse (typically 5-10 ns) and the quenching partners and coefficients are known. However, for complex gas mixtures (e.g. humid air admixtures) or measurements in open air, the quenching is very stronger and the quenching partners are not known, making absolute measurements using traditional TALIF impossible.

We present a picosecond TALIF technique with which we were able to resolve the effective lifetime of the excited state and therefore measure, rather than calculate, the quenching effects. This allows us to obtain absolute density distributions of N, O and H atoms in the effluent of an RF-driven APPJ operating in helium gas with small admixtures of oxygen, nitrogen and/or water. We find that the effective lifetime of the excited state and the ground-state densities decrease as a function of distance from the APPJ nozzle, due to diffusion of ambient air into the APPJ effluent. Furthermore, we investigated quenching effects in a APPJ with only O_2 admixtures, by comparing direct lifetime measurements, obtained with ps-TALIF, with traditional quenching calculations. We found that the experimental lifetimes were shorter than the calculated ones, which means that quenching by plasma-produced species and/or three body collisions (not taken into account in the calculation) may play a significant role.

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Invited

HEATING AND COMPRESSION OF LASER PRODUCED PLASMA IN A PULSED MAGNETIC FIELD

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The results of an experiment on heating and compression of a laser produced plasma in vacuum using a pulsed magnetic field are described. The laser plasma was produced by laser ablation of a copper (Cu) target using 248 nm 25 ns, excimer laser at 2 J cm^{-2}. A 3-turn planar induction coil, with inner and outer radii of 5 mm and 9 mm, respectively, was positioned 10 mm directly above the ablation spot and parallel to the target surface. The coil was driven by the discharge of a 0.47 µF, 1.5 kV capacitor triggered with controllable delay after the laser pulse. This gave an underdamped discharge with a period of 2.2 µs, a peak current of 1.1 kA, and a maximum magnetic field of 0.3 T at the centre of the coil. The magnetic field distribution was calculated using COMSOL Multiphysics [1]. The density and flow velocity of the plasma load through the induction coil was measured using a Langmuir ion probe [2]. The magnetic field was observed to have a strong influence on both the plasma between the coil and the target, and on the plasma which flows through the aperture in the coil. Inductive heating of the plasma is evidenced by strong enhancement of the overall visible light emission and the appearance of Cu^{+} line emission. The spectral emission was simulated using the collisional-radiative spectral analysis code PrismSPECT to find the rise in electron temperature due to inductive heating [3]. The plasma flow through the coil aperture is strongly pinched as it propagates beyond the coil (Fig. 1(c)) due to the Lorentz interaction of the induced current and the coil magnetic field.

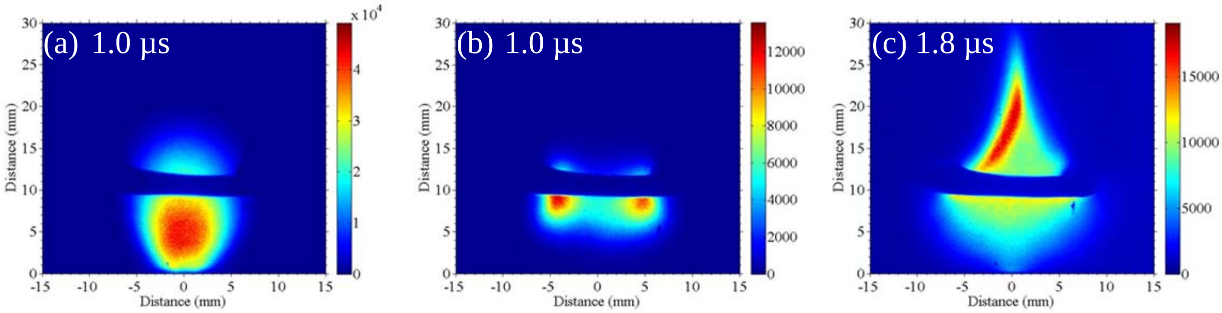

Figure 1. (a) Optical image of the ablation plume at 1.0 µs without the pulsed magnetic field. The plume emission is obscured by the coil in the region 10 - 12 mm from the target. (b), (c) Images of Cu^{+} line emission at 1.0 µs and 1.8 µs, respectively, with the pulsed magnetic field. The image at 1.0 µs (b) shows a ring of enhanced emission near the coil due to inductive heating, while the image at 1.8 µs (c) shows pinching of the plasma flowing through the coil aperture.

References

1. COMSOL Multiphysics, http://www.comsol.com
2. T. N. Hansen, J. Schou, and J. G. Lunney, Appl. Phys. A, **69**, S601 (1999)
3. PrismSPECT, http://www.prism-cs.com/Softwrae/PrismSpect/PrismSPECT.htm

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Iodine chemistry in global model and experiments

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Most state-of-the-art electric space propulsion systems such as Ion and Hall thrusters use xenon as the propellant gas. However, xenon is very rare, expensive to produce and used in a number of competing industrial applications. Alternatives to xenon are currently being investigated, and iodine has emerged as a potential candidate. Its lower cost, larger availability, its solid state at standard temperature and pressure, its low vapor pressure and its low ionization potential makes this element an attractive option. A global model of an iodine plasma inside an ion thruster has therefore been developed to compare the behavior and performances with the ones in Xenon [1]. To complete the development of the global model, a iodine reaction set has been established. However major processes included in the list are still poorly detailed. Most of the rates used in the model have therefore been calculated on demand by J. Hamilton and J. Tennyson (Quantemol).

The final list of processes contains 12 reactions, involving iodine under mono- and di-atomic form. The lowest excited state of I_2 has an energy threshold of 2.449 eV while the dissociation energy is 1.567 eV, thus we do not consider I2 excitation. We also neglect direct electron attachment to I and I_2. The iodine plasma is weakly electronegative in our case, with a constant ion temperature set equal to 0.1 eV. The neutral temperature is calculated from a gas heating equation. We used the global model to calculate plasma parameters such as neutral, ion and electron densities and electron temperature. From this we deduce the system performances such as thrust, specific impulse and efficiencies. When running with a neutral gas flow of 1 mg/s, an acceleration potential of 1000 V and RF power of 800 W, the model predicts a thrust of 30 mN for an extraction diameter of 60 mm for both iodine and xenon. The thruster efficiency is however 15% higher for iodine compared to xenon mainly due to the lower ionization energy for iodine and larger ion mass due to the contribution from I_2 ions.

Results of the iodine global model were compared with experimental data obtained under similar operating conditions. An experimental test-bench dedicated to iodine studies has been assembled with all precautions needed. Iodine is a corrosive gas and chemically active with certain metals (titanium, copper, silver, some alloys of aluminium) and this has been considered. At solid state at standard temperature and pressure, iodine is heated to sublimate, then injected inside the plasma source where the neutral gas is ionized. The whole injection system is heated to avoid condensation on surfaces and a mass flow controller allows a fine control on the neutral mass flow. A translation stage inside the vacuum chamber allows volumetric plasma studies using a cylindrical Langmuir probe. By comparing the model and experimental results, good agreements between the various densities were found at medium power, indicating that the reaction set used in the model seem relevant. A notable difference is observed for the negative density between model and experiments, which may be explained by difficulty in measuring negative ion densities by electrostatic probes. There are still open questions on the surface recombination coefficient in iodine that was here set to 0.02.

References

1. P. Grondein, T. Lafleur, P. Chabert, A. Aanesland, Physics of Plasmas, In review (2016).

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LOW TEMPERATURE PHOTOIONIZED PLASMAS DRIVEN BY LPP EUV SOURCES

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Low temperature plasmas are utilized in various technologies including plasma etching, surface treatment, thin layer deposition etc. The plasma etching processes are utilized in microelectronic technologies for the fabrication of semiconductor devices, microengineering, nanotechnology, etc. The plasma treatment of silicon surface can significantly change its reflection properties. The resulting, so called, black silicon with minimized reflectance is very important for optoelectronic devices, in particular, for high efficiency solar cells. As a result of plasma treatment photoluminescence properties of silicon nanocrystals can be also modified. Reactive etching of silica glasses allows for production of microfluidic devices.Low temperature plasmas are also formed in Space. Ionization of atoms and molecules is one of the dominant processes that occur in upper atmospheres. In case of molecules, ionization can result in further dissociation to ionic and neutral species.Ionization of O_2, N_2 and other simple molecules by solar radiation is one of the most important ion production channels on Earth's and Titan's upper atmospheres.

Low temperature plasmas for technological processes are produced using different kinds of plasma generators including inductively or capacitively coupled radio-frequency plasma reactors, microwave plasma torch, dielectric barrier discharge or electron-beam generated plasmas. In Space one of the most important processes leading to low temperature plasma formation is photoionization.This process can be also employed for creation of low temperature photoionized plasmas in laboratory.

In this work spectral investigations of low temperature photoionized plasmas were performed. The photoionized plasmas were created by irradiation of atomic or molecular gases with intense EUV (extreme ultraviolet) radiation pulses. Two laser plasma EUV sources of different parameters used in the experiments were based on 0.8 J /4ns and 10 J/ 10 ns Nd:YAG lasers respectively. Both sources operated at 10 Hz repetition rate. The EUV radiation was focused using a dedicated reflective collector onto the gas stream, injected into a vacuum chamber synchronously with the EUV pulses. Irradiation of gases resulted in photoionization of atoms or molecules followed by dissociative ionization of the molecules and various collisional and radiative processes. Energies of the driving photons were sufficient for electron impact excitation or ionization including inner shell ionization. Hollow ions being the result of inner shell collisional or photoionization relaxed mainly through an Auger effect, however, an inner shell radiative decay was also possible. All these processes led to formation of low temperature photoionized plasmasemitting electromagnetic radiation in the wide spectral range.Emission spectra were measured in the EUV and optical ranges. The EUV spectra contained multiple spectral lines, originating from singly, doubly or even triply charged ions. The UV/VIS spectra were composed of spectral lines corresponding to radiative transitions in atoms, molecules, atomic or molecularions. For analysis of the EUV spectra numerical simulationswere performed, using a collisional-radiative PrismSPECT code.Parameters of the photoionized plasmas were estimated by fitting the spectrum obtained from the simulations to the experimental one. For computer simulations of the molecular spectra measured in the UV/VIS range a LIFBASE code was employed. Apart from that, the electron temperaturesof plasmas created in different gases were estimated employing a Boltzmann plot method.

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Oral

WARM DENSE MATTER. I

X-RAY SPECTROSCOPIC STUDIES OF SOLID-DENSITY PLASMAS CREATED BY AN X-RAY FREE ELECTRON LASER

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The advent of Free-Electron-Lasers (FELs) operating in the x-ray regime, such as the Linac Coherent Light Source (LCLS), have revolutionised our ability to create and diagnose solid-density plasmas. These remarkable sources have peak spectral brightnesses a billion times greater than those of any synchrotron device, and provide the ability to irradiate matter with x-rays at intensities of order 10^{17} - 10^{20} Wcm^{-2} - a regime that was previously confined to the optical domain.

When solid-density matter is irradiated on sub-100-fsec timescales at these x-ray intensities the electrons are heated to temperatures of several hundred eV. Core holes induced in the system via photoionisation by the FEL rapidly fill and, depending on the FEL photon energy and intensity, radiation is only emitted during the FEL pulse itself: the photon energies are too great for thermal emission. In this case a time-integrated spectrum can reveal remarkable information about the state of the solid-density plasma on time-scales shorter than that required for an atom to move further than a lattice spacing: the heating is truly isochoric.

We report here on the first experiments reported where such an x-ray FEL was incident on a solid-target [1]. The aluminium sample, irradiated with photons at energies between 1560 eV and 1850 eV emits copious radiation from the various ion stages present during its heating to almost 200 eV. However, the $K - \alpha$ radiation for a given stage is only produced strongly when the photon energy of the incident FEL exceeds the K-edge energy of the ion, allowing an accurate measurement of the ionisation energy. We find that the ionisation potential is significantly depressed beyond that predicted by simple models used in many atomics-kinetics calculations [2], but is in good agreement with calculations based on density-functional-theory [3]. Further detailed study of the x-ray spectra emitted by such targets allows us to glean information on the femtosecond collisional ionisation rates [4], and to observe saturable absorption in the x-ray regime [5].

More recent studies have shown that the x-ray laser is capable of isochorically heating very thin solid density targets, just a few hundred atoms across. In this case $K-$shell radiation can be produced which is optically thin, allowing bench-mark measurements of atomic line-widths at solid density. The solid-density plasmas produced are extremely close to LTE conditions, and the x-ray laser is sufficiently stable and reproducable that the variation of emission with target thickness allows a measure of both the source function and opacity to be gleaned accurately from the data.

References

1. S.M. Vinko *et al.*, Nature, **482**, 59 (2012).
2. O. Ciricosta *et al.*, Phys. Rev. Lett. **109**, 065002 (2012).
3. S.M. Vinko, O. Ciricosta and J.S. Wark, Nature Communications **5**, 3533 (2014).
4. S.M. Vinko *et al.*, Nature Communications **6**, 6397 (2015).
5. D.S. Rackstraw *et al.*, Phys. Rev. Lett. **114**, 015003 (2015).

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Free-electron x-ray laser measurements in isochorically heated warm dense matter

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We present highly-resolved measurements of inelastic x-ray scattering spectra in ultrafast heated aluminum [1]. X-ray pulses from the seeded Linac Coherent Light Source delivering an average of 0.3 mJ of 8 keV x-ray photons in a 0.005 % bandwidth pulse, have been focused to micrometer diameter focal spots isochorically heating solid materials to temperatures up to several eV. The inelastic forward scattering spectra resolve electronic plasma oscillations that directly allow an accurate determination of the electron temperature and density indicating a strongly coupled, warm dense matter state. This accuracy enables us to extract plasma properties, which show a reduced electrical conductivity as well as a non-quadratic electron plasma oscillation dispersion relation in disagreement with the Born approximation. These properties are best described by taking into account electron-electron collisions as well as strong electron-ion collisions and dynamical screening effects that are beyond the Born approximation. First results from one-temperature density-functional theory simulations confirm these findings but simulations using two-temperatures [2] have to be applied.

References

1. P. Sperling, E. J. Gamboa, H.-K. Chung, et al., Phys. Rev. Lett. **115**, 115001 (2015).
2. U. Zastrau, P. Sperling, A. Becker, et al., Phys. Rev. Lett. **112**, 105002 (2014).

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GENERALIZED ATOMIC PROCESSES FOR WDM: XFEL INTERACTION WITH SOLIDS

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X-ray Free Electron Lasers XFEL have provided the scientific community with outstanding tools to create and study extreme states of matter: fs-time scale and micro-focusing enables photon densities in excess of solid density permitting photo-ionization of almost all inner atomic shells in a single pulse leading to a sudden transformation of a cold solid into a "hollow crystal" [1]. This highly non-equilibrium exotic state drives complex ultra-fast phenomena that are far from being understood.
Generalized atomic processes [2] are proposed to establish a consistent description from the free-atom approach to the heated and even up to the cold solid. It is based on a rigorous introduction of the Fermi-Dirac statistics, Pauli blocking factors and on the respect of the principle of detailed balance via the introduction of direct and inverse processes. A probability formalism driven by the degeneracy of the free electrons enables to establish a link of atomic rates valid from the heated atom up to the cold solid. This allows to describe photoionization processes in atomic population kinetics and subsequent solid matter heating on a femtosecond time scale.
The Auger effect is linked to the 3-body recombination via a generalized 3-body recombination that is identified as a key mechanism for XFEL matter heating. Detailed simulations are carried out for aluminum that highlight the importance of the generalized approach.

References

1. F.B. Rosmej: *"Exotic states of high density matter driven by intense XUV/X-ray Free Electron Lasers"*, "Free Electron Laser", InTech 2012, editor S. Varró, p. 187 - 212, ISBN 978-953-51-0279-3.
2. B. Deschaud, O. Peyrusse, F.B. Rosmej, EPL **108**, 53001 (2014).

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X-RAY SOURCES. I

ADVANCES IN NON-EQUILIBRIUM ATOMIC PHYSICS WITH NOVEL LASER TARGETS

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We have been developing new paths to achieve higher hard x-ray fluences for various applications. The focus of this research has been on development of new ultra-low-density pure metal foams fabricated as self-supporting structures of nanowires, and parallel development of novel metal-nanoparticle-loaded carbon nanotube foams. In this presentation I will discuss the foam development work, review the x-ray spectral emissivity data obtained from Omega and NIF laser experiments with new Cu and Ag foam targets, and compare the experimental results to those predicted by 2D simulations with a radiation-hydrodynamics code incorporating detailed non-LTE atomic models. I will show how this work has opened up two new paths to getting higher x-ray conversion efficiency at high photon energies for laser-driven x-ray sources, and helped to advance our understanding of non-equilibrium atomic physics.
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Invited

TOWARD COMPACT AND ULTRA-INTENSE LASER BASED SOFT X-RAY LASERS

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Aside from being table-top coherent EUV sources, plasma-based EUV lasers exhibit high-quality optical beam as well as a high photon number per pulse. Hitherto, the duration of these sources was limited to the picosecond range, and their polarisation to linear or unpolarised, subsequently greatly reducing the field of applications. We will show here how recent work conducted at LOA allowed to overcome these bottlenecks.

We report here recent work on an optical-field ionized (OFI), high-order harmonic-seeded EUV laser. The amplifying medium is a plasma of nickel-like krypton [1] obtained by optical field ionization focusing a 1 J, 30 fs, circularly- polarized, infrared pulse into a krypton-filled gas cell or krypton gas jet. The lasing transition is the $3d^9 4p$ (J=0) $-\!\!\rightarrow$ $3d^9 4p$ (J=1) transition of Ni-like krypton ions at 32.8 nm and is pumped by collisions with hot electrons.

The polarization of the HH-seeded EUV laser beam was studied using an analyzer composed of three grazing incidence EUV multilayer mirrors able to spin under vacuum [2]. For linear polarization, the Malus law has been recovered while in the case of a circularly-polarized seed, the EUV signal is insensitive to the rotation of the analyzer, bearing testimony to circularly polarized.

The gain dynamics was probed by seeding the amplifier with a high-order harmonic pulse at different delays [3]. The gain duration monotonically decreased from 7 ps to an unprecedented shortness of 450 fs FWHM as the amplification peak rose from 150 to 1,200 with an increase of the plasma density from 3×10^{18} cm^{-3} up to 1.2×10^{20} cm^{-3}. The integrated energy of the EUV laser pulse was also measured, and found to be around 2 μJ. It is to be noted that in the ASE mode, longer amplifiers were achieved (up to 3 cm), yielding EUV outputs up to 14 μJ.

References

[1] S. Sebban, T. Mocek, D. Ros, L. Upcraft, Ph. Balcou, R. Haroutunian, G. Grillon, B. Rus, A. Klisnick, A. Carillon, G. Jamelot, C. Valentin, A. Rousse, J.P. Rousseau, L. Notebaert, M. Pittman, and D. Hulin, "Demonstration of a ni-like kr optical-field-ionization collisional soft x-ray laser at 32.8 nm," Phys. Rev. Lett. 89, 253,901 (2002).

[2] A. Depresseux, E. Oliva, J. Gautier, F. Tissandier, G. Lambert, B. Vodungbo, J.-P. Goddet, A. Tafzi, J. Nejdl, M. Kozlova, G. Maynard, H. T. Kim, K. T. Phuoc, A. Rousse, P. Zeitoun, and S. Sebban, "Demonstration of a circularly polarized plasma-based soft-x-ray laser," Phys. Rev. Lett. 115, 083,901 (2015).

[3] A. Depresseux, E. Oliva, J. Gautier, F. Tissandier, J. Nejdl, M. Kozlova, G. Maynard, J. P. Goddet, A. Tafzi, A. Lifschitz, H. T. Kim, S. Jacquemot, V. Malka, K. Ta Phuoc, C. Thaury, P. Rousseau, G. Iaquaniello, T. Lefrou, A. Flacco, B. Vodungbo, G. Lambert, A. Rousse, P. Zeitoun, and S. Sebban, "Table-top femtosecond soft x-ray laser by collisional ionization gating," Nat Photon 9, 817–821 (2015).

INFLUENCE OF PARTIAL TEMPORAL COHERENCE ON THE SPECTRAL CHARACTERIZATION OF XUV LASER PULSES

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The last decade have seen the emergence of seeded plasma- based XUV lasers, where a femtosecond resonant high-order harmonic (HH) pulse is injected and amplified in a XUV laser plasma amplifier. The seeded mode has significantly enhanced the spatial and temporal coherence properties of these XUV lasers, and drastically reduced the pulse duration compared to the ASE (Amplification of Spontaneous Emission) mode. The properties of seeded XUV lasers pulses approach those of X-ray Free Electron Lasers (XFEL) in the same spectral range, but due to the very narrow bandwidth of the plasma amplifier (10^{11} – 10^{12} Hz) their pulse duration is limited to the picosecond. To reach the fs range in which XFEL already enable numerous applications, the XUV lasers plasma amplifier bandwidth has to be broadened.
Thus, in the past few years, the temporal coherence and the related spectral properties of collisional XUV lasers were experimentally characterized for the four types pumping techniques currently implemented worldwide: capillary discharge (CD), quasi-steady-state (QSS), transient excitation (TCE), and optical-field ionization (OFI). This comprehensive work has been carried out using the same instrument, a variable path-difference interferometer. The coherence time was inferred from a linear autocorrelation of the XUV pulse, by measuring the variation of the fringe visibility with the path difference, which yields the modulus of the degree of coherence. The spectral profile and the associated linewidth of the XUV laser is inferred through a Fourier transform of the degree of coherence, following the Wiener-Khintchin theorem [1].

The measured coherence times range between 0.5 ps and 5 ps, as a result of the different plasma parameters (temperature and density) at which the XUV lasers operate. Yet, the pulse duration of XUV lasers operating in ASE mode varies by three orders of magnitude, between a few ps (TCE and OFI), up to ~1ns (CD). Two categories of XUV lasers relevant to their partial temporal coherence, defined as to the ratio of the pulse duration and the coherence time, can then be distinguished: those with a pulse duration 100 to 1000 times longer than the coherence time, and those with a pulse duration close to the coherence time. This leads to two different behaviors observed in our experiments, which are addressed in this work.
We have used numerical simulations based on a partial coherence model developed for XFEL [2] that help to understand how the duration of the pulse relative to the coherence time can influence the shape of the measured visibility curve and affect the estimation of the spectral profile.

References

1. M. Born and E. Wolf, *Principles of Optics*, 7th edn. (Cambridge University Press, 1999)
2. T. Pfeifer et al., Opt. Lett. **35**, 3441 (2010).

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Oral

Tunable EUV radiation source for Laboratory Based Photoemission Spectro-Microscopy

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This project aims for the development of a high-flux extreme ultraviolet gas-discharge lab-source, which is competitive in terms of tunability and flux with synchrotron sources in a photon energy range of 30 – 300 eV. For this purpose extreme ultraviolet radiation from hot plasmas of low- and medium-Z elements is going to be studied and used. The characteristic width of plasma emission lines is estimated to satisfy the PES requirements. The desirable lines, however, must be discriminated from the whole spectrum by a grating- or Bragg mirror monochromator. The tuning of the photon energy is possible by the use of different emission lines, by changing working gases, or by the use of mixture of gases.

Besides high spectral radiance, the tunability of the photon energy is the key aspect, which makes the synchrotron superior to other sources. Powerful lab-sources are highly desirable, since synchrotrons are very limited in availability and often strong restrictions to experimental conditions apply due to their multi-purpose beamlines equipment.

Recently, we selected 71.7 eV photon energy from the oxygen spectrum (O^{5+} spectral line) of our high power gas-discharge EUV source for photoelectron imaging in the direct- and k-space to map the band structure of a Au (111) single crystal surface and studied the surface oxidation on islands of the phase-change material GeSbTe (GST) by performing highly surface-sensitive spectro-microscopy.

Future plans include general plasma spectroscopy, e.g. measurements of time resolved spectra, determination of plasma temperature and duration of emission, aiming at the search of the source regimes applicable for PES at multiple photon energies.

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X-RAY EMISSION GENERATED BY LASER-PRODUCED PLASMA FROM DIELECTRIC NANOSTRUCTURED TARGETS

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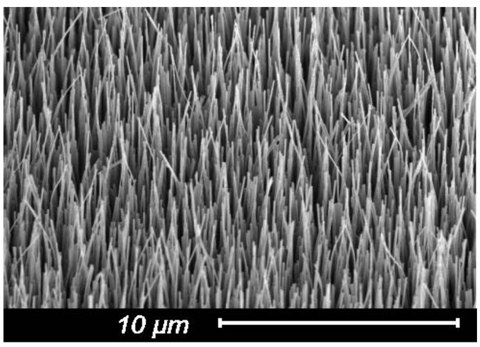
In this contribution we present the results of experimental investigation of hard X-ray generation from nanostructured solid targets irradiated by relativistically intense ultrashort laser pulses. In experiments 45 fs, 130 mJ laser pulses at 400 nm wavelength were focused close to the normal incidence onto a nanostructured target providing the peak intensity of 2.7×10^{19} W/cm^2. For these experiments it is essential to have a high pulse contrast, which is about 10^{-10} at 1 ps before the pulse peak. The nanostructured targets were synthesized using a thermal transport technique of zinc oxide, a dielectric material, transparent in the visible and NIR/MID range. The samples have morphology of a disordered array of single crystalline nanowires (“grass-like”) with diameters of 100-400 nm and a length of 1-4 μm (Fig. 1(a)). For investigating the influence of the morphology on the x-ray yield, we have also measured x-ray spectra emitted from polished single crystalline ZnO. The observed characteristic transition lines in the 8.7-9.0 keV spectral energy region demonstrate generation of highly charged states of Zn up to He-like Zn from both, nanostructured and polished sample (Fig. 1(b)). However, the obtained flux of photons at the K_α transitions in He-like Zn is more than 2.5 times higher for nanostructured targets in comparison with a polished sample. Remarkably, the observed K_α emission from Zn^{28+} generated in nanostructured target has almost the same intensity as the K_α emission from neutral Zn, pointing on the possibility to achieve highly charged high density plasma. Measurements with samples having different length and diameter of nanowires have shown that the longer and the thinner wires are advantageous for the production of hot and dense plasma. To get insight into the temporal evolution of plasma generated from the nanostructured targets, we present simulations of experimental spectra using FLYCHK code with time-dependent electron density and temperature.

(a)



(b)

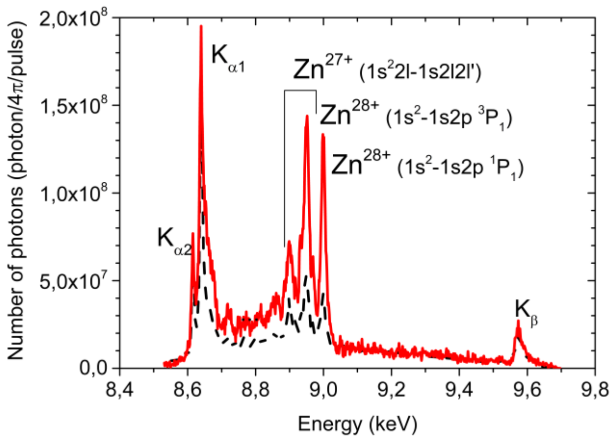


Fig. 1. (a) SEM image of a “grass-like” nanostructured ZnO sample. (b) Calibrated spectra of X-ray emission obtained from a “grass-like” (red solid line) and polished (black dashed line) ZnO targets.

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LOW TEMPERATURE PLASMAS. II

STATE-TO-STATE MODELING OF NON EQUILIBRIUM LOW TEMPERATURE ATOMIC PLASMAS

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The modeling of plasmas in thermodynamic non equilibrium requires the development of dedicated kinetic mechanisms. Even if heavy particles are less effective than electrons from the collisional point of view to induce substantial changes in the plasma composition, the sometimes low ionization degree leads to take them into account in the mechanism. The non equilibrium degree can even be sufficiently high to prevent a satisfactory coupling between the excited atomic and molecular states. The excited states then behave freely due to the different elementary electron and heavy particle induced collisions. The modeling becomes very challenging since different types of collisional elementary processes are involved, whose collision partners can follow an energy distribution function at different temperatures if the concerned distributions are Maxwellian. The difficulty is increased if the plasma density is sufficiently low to induce a significant influence of the radiative elementary processes on the excited states. The set of elementary data relative to the collisional and radiative processes forms a Collisional-Radiative (CR) model and can be implemented in a State-to-State (StS) modeling of the plasma in order to reproduce its behaviour.

Two situations remarkably illustrate the benefit provided by such a sophisticated strategy.

(1) **Laser-induced plasmas**. The interaction between a powerful laser pulse and a solid sample generally leads to its absorption by the target, the temperature of which sufficiently increases to induce a phase change. The pulse characteristic time typically ranges from the femtosecond to the nanosecond regime, which leads to different elementary processes within the sample. The finally produced plasma is at a temperature of some 10^4 K and its density is strong enough to induce a pressure of the order of 10^{11}-10^{12} Pa [1]. Then, a very rapid expansion of the plasma is observed, with the production of a shock wave propagating in the background gas if its density is sufficiently high. In this context, the plasma departs from equilibrium during its evolution. The most relevant way to model it is to develop a StS approach coupled with a CR model, if the plasma – in part composed of the sample material – is spectroscopically analysed in order to deduce its composition.

(2) **Atmospheric entry plasmas**. During the hypersonic entry of a spacecraft in the upper layers of a planetary atmosphere, the sudden decrease in the velocity close to the fuselage leads to the formation of a shock layer where temperature and density are much higher than at the upstream. The dissociation and ionization degrees can easily reach unity [2]. The resulting heat exchange to the wall (by convection, parietal chemistry and radiation) can damage it. Beyond the possible experiments performed on ground test facilities to validate materials for the elaboration of efficient thermal protection systems, modeling can be advantageously developed in order to reveal the impact of the plasma characteristics and particularly its departure from equilibrium on the heat exchange. Then, the choice of the best thermal protection system can also be validated from a more theoretical point of view.

These examples illustrate the interest of StS approaches and CR models elaborations. They will be thoroughly described.

References

1. V. Morel, A. Bultel, J. Annaloro, C. Chambrelan, G. Edouard, C. Grisolia, Spectrochim. Acta Part B **103-104**, 112 (2015).
2. J. Annaloro and A. Bultel, Phys. Plasmas **21**, 123512 (2014).

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Ab initio methods for core level spectra simulation of hydride molecular ions

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Molecular ions play a major role in the interstellar chemistry since they act as initial products which lead to the formation of larger molecules [1]. Furthermore, the spectroscopic studies of these ions provide unique identification of atomic/molecular species and their relative abundances in astrophysical environments.

In this context, we will present a combined experimental and theoretical study of K- and L-shell photoabsoprtion spectroscopy of simple hydride molecular ions of carbon, oxygen and silicon. Experimentally, molecular ions were produced in a permanent magnet electron cyclotron resonance (ECR) ion source and photoabsorption spectra of the ions were measured with a photon-ion merged beam setup at the synchrotron facility SOLEIL. Furthermore, we simulate the photoabsorption spectrum of molecular ions using a combination of post Hartree-Fock and nuclear wavepacket methods. In particular, the calculations of the potential energy and dipole transition curves were performed using the Configuration Interaction method and Spin-orbit coupling was taken into account through the Breit-Pauli operator. We consider the impact of metastable (singlet and triplet) electronic states, which are present in the experimental ion beams, on the photoabsorption spectra. Furthermore, we investigate thoroughly the nature of the electronic dipolar transitions to clarify the structure of the spectra.

The theoretical results compare quantitatively with the experimental ones and allow the attribution of the experimental spectroscopic lines and the population of the lowest singlet and triplet states. The proposed combined approach can readily be applied to other molecular ions and opens new perspectives in the nascent field of the photoionization of molecular ions in gas phase.

1. Smith, D Phil. Trans. R. Soc. Lond. **1988**, A324, 257-273

Emission of fast non-Maxwellian hydrogen atoms in low-density laboratory plasmas

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The source of strong and broad emission of the Balmer-α lines in mixes of hydrogen and noble gases in front of metallic surfaces is a subject of controversial discussion of many plasma types [1,2]. In this work the excitation source of the Balmer lines is investigated by means of optical emission spectroscopy in the plasma device PSI-2 [3]. Neutral fast non-Maxwellian hydrogen atoms are produced by acceleration of hydrogen ions towards an electrode immersed into the plasma. By variation of the electrode potential the energy of ions and in turn of the reflected fast atoms can be varied between 50 to 300 eV. The fast atoms in front of the electrode are observed simultaneously by an Echelle spectrometer ($0.001\,\mathrm{nm/channel}$) and by an imaging spectrometer ($0.01\,\mathrm{nm/channel}$) up to few cm in the plasma. The strongest excitation channel of the Balmer lines is observed for Ar-H mix plasmas and second intense for Kr-H mix plasmas. Mixing hydrogen with other noble gases (Ne, He or Xe) the effect is weaker by more than one order of magnitude. It is shown, that the key process, impacting this emission, is the binary collision between the fast neutral hydrogen atom and the noble gas atom. Two possible sources of excitation are discussed in details: one is the excitation of hydrogen atoms by argon atoms in its ground state and the second one is the process of the so-called *excitation transfer*. In the latter case the excitation is stimulated by the metastable states of argon atoms. The excitation transfer from Ar metastable to production of enhanced Ly-α emission has been observed for instance in Ref. [4], however, the atomic data for Balmer lines emission production could be hardly found in literature.

References

1. T. Babkina et al., Europhys. Lett. **72**, 235 (2006).
2. N.M. Šišović et al., Eur. Phys. J. D **32**, 347 (2005).
3. A. Kreter et al., Fusion Sci. Technol. **68**, 8 (2015).
4. M.A. Clyne et al., Chemical Physics **47**, 179 (1980).

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A TRIBUTE TO CLAIRE AND JACQUES BAUCHE

A SURVEY ON INTERPRETING ATOMIC SPECTRA IN THE VICINITY OF CLAIRE AND JACQUES BAUCHE

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The theoretical analysis of atomic spectra went through huge changes in the past 50 years. After the introduction of tensor operator methods by Brian Judd at LaboratoireAimé Cotton (LAC) in the early 60's and several years of applications to the interpretation of fine and hyperfine structures in neutral and singly ionized elements, mostly with f^n unfilled subshells, theoreticians at LAC have met many teams already active in the field of multi-charged ions. Among the first of them were the NBS (NIST), Washington and the Hebrew University, Jerusalem, shortly followed by the Institute of Spectroscopy, ISAN, Troitsk, the group at tokamak TFR and the teams of laser produced plasmas at EcolePolytechnique, Palaiseau. Semi-empirical methods combining least squares fitting of energy levels (as done by Racah's team in iron group elements) and isoelectronic regularities following Edlén helped for accurate predictions of level energies in moderately charged ions. In ions of higher charge, the relativistic parametric potential method (RELAC code) led to straight comparison between experimental and calculated spectra. The Racah-Slater parametric method is now practiced by means of the Cowan codes with the support of Hartree-Fock evaluations of radial integrals for ensuring physical reliability. Recent studies initiated at Observatoire de Paris-Meudon deal with free ion spectra of species with applications (Nd^{3+}, Tm^{3+}, Er^{3+}). After years, atomic structure calculations are back in the field of neutral and singly ionized lanthanide elements as a step in the study of cold atoms and molecules.

Invited

STATISTICAL PROPERTIES OF LEVELS AND LINES IN COMPLEX ATOMIC SPECTRA

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We review recent developments of the statistical properties of complex atomic spectra, based on the pioneering work of Claire and Jacques Bauche. The first part of the talk is devoted to several improvements of the statistical methods (UTA, SOSA) for the modeling of the lines in a transition array: impact of high-order moments and choice of the distribution (Generalized Gaussian, Normal Inverse Gaussian), corrections at moderate or low temperatures and interaction between relativistic subconfigurations.

The second part of the talk concerns exact or statistical methods for determining the distribution of the *M* values (projection of total angular momentum *J*) in an electron configuration. This distribution, written *P(M)*, may be used to calculate the allowed values of *J* and the number of electric dipole lines between two configurations. We have shown that *P(M)* can be computed exactly using an efficient recursive technique. The statistical modeling of *P(M)* introduced by J. and C. Bauche was also extended in order to account for configurations with a high-ℓ spectator and a new analytical formula for the evaluation of the number of E1 lines with a wider range of applicability was derived. Analytical formulas for the estimation of the number of E2 lines in a transition array as well as a generalized "*J*-file" sum rule for E2 lines and the strength-weighted shift and variance of the energies of the inter-configuration E2 lines of $n\ell^{N+1} \rightarrow n\ell^{N}\, n'\ell'$ were also obtained.

The distributions of levels and lines may reveal unexpected and surprising regularities and trends. We discuss some of them, such as Learner's law, which indicates that the number of lines with a given intensity is roughly inversely proportional to the square root of that intensity. We also show that generating functions can be useful to study the distributions of quantum numbers, such as the odd-even staggering in the *J* values of atomic configurations.

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SOME REMARKS ON GLOBAL METHODS FOR THE MODELING OF ATOMIC PHYSICS IN HOT PLASMAS

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Atomic physics is involved in the plasma context for a proper evaluation of various quantities such as charge state distribution, radiative properties (i.e. emissivity or opacity), etc…These derived quantities are in turn used for the calculation of transport properties, spectroscopic diagnostics, etc…

The difficulty is that one faces situations of different complexities, from simple nearly closed-shell configurations to open-shell many-electron configurations. This is the field of complex-atom physics in which Jacques and Claire Bauche made many important contributions concerning the emerging properties from large ensemble of levels. These contributions concern the existence of statistical laws for
- ensembles of levels,
- ensembles of spectral lines,
- the transition rates between ensembles of levels.

These ensembles can be configurations, superconfigurations or compound configurations (mixed by CI)

This talk will review some of these laws and their consequences concerning applications such as the charge state distribution in plasmas, the radiative properties or the emergence of effective temperatures.

Transition Arrays:Unresolved or Resolved?

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Transition Arrays (TA) appear in the spectra of medium to high Z ionized atoms in hot plasmas. This talk will focus on opacities of TA for simulations of ICF and astrophysical plasmas. TA are unavoidable data in the evaluation of Rosseland and Planck mean opacities. I will address the dilemma of choice between different approaches - from Unresolved (UTA),which are quick, but which may loose important features- to fully resolved TA in Detailed level Account(DLA) with Configuration interaction(CI) -which might be very laborious but necessary in some cases. I will review several intermediate models (STA, CRSTA, RTA,PRTA, MUTA, etc…). The choice depends on the requirements of the simulation and the feasibility.
This work was done in collaboration with Michel Busquet.

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Emission of fast non-Maxwellian hydrogen atoms in low-density laboratory plasmas

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The source of strong and broad emission of the Balmer-α lines in mixes of hydrogen and noble gases in front of metallic surfaces is a subject of controversial discussion of many plasma types [1,2]. In this work the excitation source of the Balmer lines is investigated by means of optical emission spectroscopy in the plasma device PSI-2 [3]. Neutral fast non-Maxwellian hydrogen atoms are produced by acceleration of hydrogen ions towards an electrode immersed into the plasma. By variation of the electrode potential the energy of ions and in turn of the reflected fast atoms can be varied between 50 to 300 eV. The fast atoms in front of the electrode are observed simultaneously by an Echelle spectrometer ($0.001\,\mathrm{nm/channel}$) and by an imaging spectrometer ($0.01\,\mathrm{nm/channel}$) up to few cm in the plasma. The strongest excitation channel of the Balmer lines is observed for Ar-H mix plasmas and second intense for Kr-H mix plasmas. Mixing hydrogen with other noble gases (Ne, He or Xe) the effect is weaker by more than one order of magnitude. It is shown, that the key process, impacting this emission, is the binary collision between the fast neutral hydrogen atom and the noble gas atom. Two possible sources of excitation are discussed in details: one is the excitation of hydrogen atoms by argon atoms in its ground state and the second one is the process of the so-called *excitation transfer*. In the latter case the excitation is stimulated by the metastable states of argon atoms. The excitation transfer from Ar metastable to production of enhanced Ly-α emission has been observed for instance in Ref. [4], however, the atomic data for Balmer lines emission production could be hardly found in literature.

References

1. T. Babkina et al., Europhys. Lett. **72**, 235 (2006).
2. N.M. Šišović et al., Eur. Phys. J. D **32**, 347 (2005).
3. A. Kreter et al., Fusion Sci. Technol. **68**, 8 (2015).
4. M.A. Clyne et al., Chemical Physics **47**, 179 (1980).

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ATOMIC DATA AND PROCESSES. II

CAN QUANTUM CHAOS PREVENT NUCLEAR FUSION?

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Tungsten is the choice material for plasma-facing components of ITER, such as the diverter. The latter is expected to work under extreme conditions, e.g., temperatures of up to 3000 degrees and high neutron irradiation. Naturally, some tungsten ions will be escaping the surface and contaminating the core plasma. For plasma temperatures between 100 eV and 10,000 eV, tungsten ions in a wide range of charge states are present, from +10 to +60. It has been found that these ions are very effective at removing electrons from the plasma in the process of recombination, which leads to cooling of the plasma by radiation. Contrary to naive expectations, electron collisions with multicharged ions stripped of 20 or so electrons are very different to the electron collisions with a bare nucleus of comparable charge. In particular, the electron-ion recombination rates can exceed those due to direct single-particle radiative recombination by a factor of 1000.

In [1,2] we showed that the origin of this enhancement, observed in Au^{25+}, U^{28+} and similar ions is due to a quantum-chaotic behaviour of the system. When the incident electron is captured by the ion, it quickly shares its energy with other electrons, becoming "entangled" in a many-body chaotic compound states. The level density of such states in complex systems is extremely large. This makes direct brute-force computation of the the processes involving such states impossible. However, the quantum-chaotic behaviour of the system allows one to develop a statistical theory [3,4], which enables one to compute the important properties of the system, e.g., the electron-ion recombination rate. Such data are crucial for modelling reactor plasmas and for the feasibility of fusion itself.

Application of the theory to tungsten ions W^{q+}, $q = 18$–25, showed that the recombination cross sections at low energy are 2–3 orders of magnitude greater than those due to the direct radiative recombination [4], and that our data for W^{20+} [5] are in agreement with the measurements [6]. We have now also developed a level-resolved quantum statistical theory of electron capture into many-electron compound resonances by performing limited diagonalisation of dielectronic "doorway" states [7]

Our statistical theory can be applied to other systems and processes which involve many-body quantum-chaotic behaviour, e.g., compound nuclei formed by neutron capture, or intramolecular vibrational energy redistribution in polyatomic molecules which is key to most chemical reactions [8].

References

1. G. F. Gribakin, A. A. Gribakina, and V. V. Flambaum, Aust. J. Phys. **52**, 443 (1999).
2. G. F. Gribakin and S. Sahoo, J. Phys. B **36**, 3349 (2003).
3. V. V. Flambaum, A. A. Gribakina, G. F. Gribakin, and C. Harabati, Phys. Rev. A **66**, 012713 (2002).
4. V. A. Dzuba, V. V. Flambaum, G. F. Gribakin and C. Harabati, Phys. Rev. A **86**, 022714 (2012).
5. V. A. Dzuba, V. V. Flambaum, G. F. Gribakin, C. Harabati, and M. G. Kozlov, Phys. Rev. A **88**, 062713 (2013).
6. S. Schippers *et al.*, Phys. Rev. A **83**, 012711 (2011).
7. J. C. Berengut, C. Harabati, V. A. Dzuba, V. V. Flambaum, and G. F. Gribakin, Phys. Rev. A **92**, 062717 (2015).
8. V. V. Flambaum, M. G. Kozlov, and G. F. Gribakin, Phys. Rev. A **91**, 052704 (2015).

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The Tungsten Project: Dielectronic Recombination data for Collisional-Radiative Modelling in ITER — W^{44+}–W^{74+}.

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Tungsten has been chosen as a plasma facing component in the divertor of the upcoming ITER magnetic confined fusion experiment, due to its ability to withstand high power loads. Having such high-Z elements as Tungsten (Z=74) in the plasma may lead to undesirable effects such as dilution and large a radiation fraction which may quench the plasma in extreme cases. The collisional-radiative modelling of Tungsten in a finite-density plasma is of key importance to understanding and ultimately controlling these effects. Modelling of these effects requires high quality, partial final-state-resolved dielectronic/radiative recombination (DR/RR) data. DR data of this quality exists only for a handful of ions, such as W^{20+} [1], W^{56+} [2], W^{63+} [3], and W^{64+} [4]. In addition, recombination data covering the entire isonuclear sequence of Tungsten has been calculated by [5] and [6] using the average ion method and the Burgess General Formula/Burgess–Bethe General Program, respectively. RR rate coefficients have been calculated for the entire isonuclear sequence by [7].

The Tungsten Project is an effort to calculate partial and total DR/RR rate coefficient data for the isonuclear sequence of Tungsten using the Breit–Pauli code AUTOSTRUCTURE [8], which has been verified experimentally with measurements from the Heidelberg Test Storage Ring [9]. We have previously reported on the progress of this project in [10], where we calculated DR rate coefficients for W^{56+}–W^{73+} in intermediate coupling (IC) and configuration average (CA). In this current work, we focus on new results for W^{44+}–W^{55+} in IC and CA, and make comparisons to currently available data for these ions. In turn, we look at the effect of the new data on the Tungsten ionization balance over W^{44+}–W^{74+}. The DR/RR data will be made available via OPEN-ADAS in the standard adf09 and adf48 formats.

References

1. N. R. Badnell, C. P. Ballance, D. C. Griffin, and M. O'Mullane, Phys. Rev. A 85, 052716 (2012).
2. A. Peleg, E. Behar, P. Mandelbaum, and J. L. Schwob, Phys. Rev. A 57, 3493 (1998).
3. U. I. Safronova, A. S. Safronova, and P. Beiersdorfer, ADNDT 95, 751 (2009).
4. E. Behar, P. Mandelbaum, and J. L. Schwob, Phys. Rev. A 59, 2787 (1999).
5. T. Pütterich, R. Neu, R. Dux, A. D. Whiteford, M. O'Mullane, and the ASDEX Upgrade Team, Plasma Physics and Controlled Fusion 50, 085016+ (2008).
6. A. R. Foster, On the Behaviour and Radiating Properties of Heavy Elements in Fusion Plasmas, Ph.D. thesis, University of Strathclyde, http://www.adas.ac.uk/theses/foster thesis.pdf (2008).
7. M. B. Trzhaskovskaya, V. K. Nikulin, and R. E. H. Clark, ADNDT 96, 1 (2010).
8. N. R. Badnell, Computer Physics Communications, 182, 1528, (2011).
9. K. Spruck, N. R. Badnell, C. Krantz, O. Novotny, A. Becker, D. Bernhardt, M. Grieser, M. Hahn, R. Repnow, D. W. Savin, A. Wolf, A. Müller, and S. Schippers, Phys. Rev. A 90. 032715 (2014)
10. S. P. Preval, N. R. Badnell, M. O'Mullane, JPCS, 635, 022068 (2015).

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STATUS OF QED TESTS IN HIGH-Z FEW ELECTRON IONS

P. Indelicato

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In this talk I will review present status of QED calculations and experiments in high-Z few electron ions, from hydrogen-like to boron-like. I will focus on n=2 to n=1 transitions and on the n=2 fine structure. I will give a survey of recent experiments performed with Electron Beam Ion Trap (EBIT) and Electron-Cyclotron Ion Sources (ECRIS), and describe the interplay between the plasma conditions in these sources and the observed transitions. I will discuss the impact on future experiments of the possibility to prepare ultra-cold plasma of highly charged ions.

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HIGH ENERGY DENSITY PLASMAS. II

X-RAY SPECTROSCOPY OF INERTIAL CONFINEMENT FUSION PLASMAS

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During the last decade x-ray spectroscopy of inertial confinement fusion plasmas that contain a spectroscopic tracer added to the fuel has made significant contributions to the diagnosis and understanding of implosion physics. This impact is based on new instrumentation and measurement techniques as well as theory and modelling calculations to interpret and analyze the data that take into account collisional-radiative atomic processes and kinetics, detailed Stark-broadened spectral line shapes including ion dynamics effects, and spectroscopic quality radiation transport. The temperature and density sensitivity of the emergent line intensity distribution of the tracer element combines the temperature and density dependence of the atomic level population distribution and the density dependence of the Stark-broadened line profiles. We discuss the analysis of spatially averaged plasma conditions in the implosion core determined from streaked argon K-shell spectra observations, its connection with the thermodynamics of the core, and the determination of the temperature and density in the compressed shell that confines the core from titanium absorption spectra [1,2]. In addition, we also discuss the development and application of several methods to unfold the spatial structure of the core using narrow-band images and a family of gated, spatially resolved spectra [3,4]. These data are obtained from an array of spectrally resolved images recorded with a unique x-ray monochromatic imaging instrument.

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References

1. R. Florido, R. C. Mancini, T. Nagayama, R. Tommasini, J. A. Delettrez and S. P. Regan, Physics of Plasmas **21**, 102709 (2014)
2. H. M. Johns, R. C. Mancini, P. Hakel, T. Nagayama, V. A. Smalyuk, S. P. Regan and J. Delettrez, Physics of Plasmas **21**, 082711 (2014)
3. L. A. Welser-Sherrill, R. C. Mancini, J. A. Koch, N, Izumi, R. Tommasini, S. W. Haan, D. A. Haynes, Jr., I. E. Golovkin, J. J. MacFarlane et al, Physical Review E **76**, 056403 (2007)
4. T. Nagayama, R. C. Mancini, R. Florido, D. Mayes, R. Tommasini, J. Koch, J. Delettrez, S. Regan and V. Smalyuk, Physics of Plasmas **21**, 050702 (2014)

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Invited

NON-LTE MODELING OF RADIATIVELY-DRIVEN DENSE PLASMAS

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There are now several experimental facilities that use strong X-ray fields to produce plasmas with densities ranging from ~1 to ~10^3 g/cm^3. Large laser facilities, such as the National Ignition Facility (NIF) and Omega reach high densities with radiatively-driven compression, short-pulse lasers such as XFELs produce solid density plasmas on very short timescales, and the Orion laser facility combines these methods. Despite the high densities, these plasmas can be very far from LTE, due to the large radiation fields and/or short timescales, and simulations mostly use collisional-radiative (CR) modeling which has been adapted to handle these conditions.

These dense plasmas present challenges to CR modeling. Ionization potential depression (IPD) has received much attention recently as researchers work to understand experimental results from LCLS and Orion [1,2]. However, incorporating IPD into a CR model is only one challenge presented by these conditions. Electron degeneracy and the extent of the state space can also play important roles in the plasma energetics and radiative properties, with effects evident in recent observations [3,4]. We discuss the computational issues associated with these phenomena and discuss methods for handling them.

References

1. O. Ciricosta, S.M. Vinko, H.-K. Chung, *et al*, Phys. Rev. Lett. **109**, 065002 (2012).
2. D.J. Hoarty, P. Allan, S.F. James, *et al*, Phys. Rev. Lett. **110**, 265003 (2013).
3. S.P. Regan, R. Epstein, B.A. Hammel, *et al*, Phys. Rev. Lett. **111**, 045001 (2013).
4. L.A. Pickworth, B.A. Hammel, V.A. Smalyk, *et al*, submitted to Phys. Rev. Lett.

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Invited

PC SPECTRA ANALYSIS OF L-SHELL COPPER *X*-PINCH PLASMA PRODUCED BY THE COMPACT GENERATOR OF ECOLE POLYTECHNIQUE

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Principal Component Analysis (PCA) is applied and compared with the line ratios of special Ne-like transitions for investigating the electron beam effects on the *L*-shell Cu synthetic spectra[1]. PCA of *L*-shell Cu are extracted over a non-LTE collisional radiative *L*-shell Cu model with and without presence of hot electrons to discuss the electron beam effects. Furthermore, PC spectra of Ne-like, F-Like and Na-Like transitions are also studied as an alternative diagnostics to investigate the polarization sensitivity of these transtions[2,3]. The extracted PCs are used to estimate the plasma electron temperature, density and beam fractions from a representative time integrated spatially resolved *L*-shell Cu *X*-pinch plasma spectrum[4,5]. The experimental spectrum is produced by the explosion of 25-µm Cu wires on a compact *LC* (40 kV, 200 kA, 200 ns) generator[5]. The modeled plasma electron temperatures are about T_e~125 eV and $N_e=7\text{x}10^{19}$ cm^{-3} in the presence of the fraction of the beams with f~0.01 and centered energy of ~10 keV.

1. L. Wang, et al., "Principal component analysis of the Spitzer IRS spectra of ultraluminous infrared galaxies", Monthly Notices of the Royal Astronomical Society, 411, 2011, pp. 1809-1818.
2. A. S. Safronova, et al., "Spectroscopic modeling of radiation from Cu and Mo X-pinches produced on the UNR 1MA Zebra generator." Journal of Quantitative Spectroscopy and Radiative Transfer 99, 2006, pp. 560-571.
3. E. O. Baronova , J Larour , F B Rosmej and F. Y.Khattak, "Polarization analysis of CuXX-lines emitted from *X*-pinch " 2015 J. Phys.: Conf. Ser. 653 012145
4.M. Fatih Yilmaz, Alaa Eleyan, Leonid E. Aranchuk and Jean Larour, "Spectroscopic analysis of X-pinch plasma produced on the compact LC-generator of Ecole Polytechnique using artificial neural networks", High Energy Density Physics, 12, 2014, pp. 1-4.
5. L. E. Aranchuk and J. Larour, "Submicrosecond X-pinch as a source of point-like radiation and multi-charged hot plasma", 15th International Conference on High-Power Particle Beams (BEAMS), July 18-23, 2004, pp. 750-753.

SIMULTANEOUS X AND XUV OPACITY MEASUREMENTS IN DENSE PLASMAS

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We present the recent experimental work at the LULI-2000 facility about X and XUV opacity measurements in mid-Z laser produced plasma. The aim of this work is, to simultaneously measure absorption structures in X and XUV ranges providing thus two different approaches to estimate the in-situ plasma temperature and validate with better accuracy the atomic physic codes. We are interested in plasma conditions characterized by temperatures between 20 eV and 25 eV and densities of the order of magnitude of 10^{-3}g/cm^3 to 10^{-2}g/cm^3. We investigate the Ni, Fe, Cr and Cu 2p-3d X-ray absorption structures whose position is dependent of plasma temperature. Furthermore, under these conditions, in mid-Z plasma the Planck and Rosseland average opacities are often dominated by XUV $\Delta n=0$ (n=3) transitions, and the strength of these structures is also highly sensitive to plasma temperature. During this experiment, we also study X-ray 2p-nd transitions, with n>3, by using samples with bigger areal masses.

The experimental scheme is based on an indirect heating of multilayer thin foils by two gold cavities heated by two nanosecond doubled-frequency 300 J beams. The temperature gradient inside the foil is reduced during the spectroscopic measurement because of both-side irradiation of the foil by the cavities. So we consider the mid-Z plasma is close to the local thermodynamic equilibrium. This plasma is probed by an X-ray backlight source created by a gold foil heated by a third nanosecond beam with an energy E~20-40 J. This backlight source is directly recorded in X-ray and XUV ranges by two different spectrometers. Simultaneously a third spectrometer composed by two independent tracks detects the signal passed through the thin foil also in X-ray and XUV ranges. So with these four measurements, we can observe the absorption of the different materials in the two ranges.

In addition to the main spectrometers, three other diagnostics are used. An independent measurement of the radiative temperature of the cavities is performed with a broad-band time-resolved spectrometer. A time-integrated spectrometer with high spatial and spectral resolution is used to compare the balanced emissivity of each cavity during the shots. Finally a pinhole camera is placed to observe the X-ray emission of the cavities and the backlight source in order to check their alignment. The association of all these diagnostics allowed us to better characterize the sample and precise the interpretation of the opacity data.

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M-SHELL RESOLVED HIGH-RESOLUTION X-RAY SPECTROSCOPIC STUDY OF TRANSIENT MATTER EVOLUTION DRIVEN BY HOT ELECTRONS IN KJ-LASER PRODUCED PLASMAS

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Hot electrons are of key importance for high intensities laser produced plasmas. Although numerous studies have contributed to this subject, it is still difficult to simulate their behaviour due to the complex non-equilibrium physics involved. Improving our knowledge about hot electrons is also of general interest for plasma physics and numerous applications (fusion sciences, etc.).

Simulations of the radiative properties indicate that atomic physics is very sensitive to hot electrons. This in turn provides the possibility for their detailed characterization by high-resolution spectroscopic methods. Of particular interest is X-ray spectroscopy due to reduced photo-absorption in dense matter and their direct efficient generation by hot electrons (inner-shell ionization/excitation).

We report on an experimental campaign conducted at the ns, kJ laser facility PALS, Prague, Czech Republic in order to study the near solid density matter evolution via hot electrons induced Kα X-ray emission. Thin copper foils have been irradiated with 1ω and 3ω pulses. Two spherically bent quartz Bragg crystal spectrometers with high spectral ($\lambda/\delta\lambda > 5000$) and spatial resolutions ($\delta x \approx 30$ μm) have been set up simultaneously to achieve a high level of confidence for the analysis of the complex K_α emission group. This group is created by the Kα emission of copper low ionization states.

In particular, we have identified emission on the red wing of the $K_{\alpha 2}$ transition ($\lambda = 1.5444$ Å) that could be identified with complex atomic structure calculations that include configuration interaction and intermediate coupling. We also analyze the influence of N and M-shell spectator electrons on Kα-copper satellites emission group. Finally, we discuss possible implications for the analysis of non-equilibrium phenomena and present first atomic physics simulations.

** This work has been done within the LABEX Plas@par project, and received financial state aid managed by the Agence nationale de la recherche, as part of the programme "Investissements d'avenir" under the reference ANR-11-IDEX-0004-02.

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WARM DENSE MATTER. II

CLASSICAL MOLECULAR DYNAMICS FOR NON EQUILIBRIUM CORRELATED PLASMAS.

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Transitions induced by intense fs X-ray pulses drive the system highly out of equilibrium resulting in very complex matter heating and sample damage: cold solid matter transforms to warm dense matter and then to a dense strongly coupled plasma. When matter is exposed to extreme conditions the electromagnetic interaction (in particular the Coulomb force) between charged particles results in a collective behavior of interacting electrons and ions. At low temperatures and high densities, the Coulomb energy may exceed the thermal energy and the particles are strongly correlated resulting in a geometrical ordering that impacts directly on the atomic structure. E.g., as particle density increases, mean distances between the particles become smaller than the mean atom radius thereby shifting the bound states towards the continuum. Consequently the number of bound states becomes finite and correlated with continuum lowering, line shifts and line broadening. The partition function and therefore all thermodynamic properties of the system are also modified.

In this context, a classical molecular dynamics code, the BINGO-TCP code [1], has been recently developed to simulate neutral multi-component (various charge state ions and electrons) plasmas. This technique involves the mechanism of collisional ionization recombination necessary to simulate plasmas with a definite temperature and equilibrated populations of ions of various charge states. As the particle environment is explicitly described, this method gives access to different quantities of interest (electric microfields, structure factors, etc.) and their statistical static and dynamics properties.

Among other properties, we report here investigation on the ionization potential depression (IPD) of an ion in dense plasmas at and out of equilibrium [2,3]. The IPD is somehow an average quantity that characterized the global effect of the plasma on that ion. Quantum properties, e.g. the ionization potential of an ion, are modified due to the interaction of the valence electron with the whole of the surrounding charges. The collisional ionization recombination model gives access to a measure of such modification. The proposed method appears to be an important tool to provide data for discussion on IPD models.

References

1. A. Calisti, S. Ferri, D. González-Herrero, M.A. Gigosos, C.Mossé and B. Talin, in preparation.
2. A. Calisti, S. Ferri, B. Talin, Contrib. Plasma Phys. **5**, 360 (2015).
3. A. Calisti, S. Ferri, B. Talin, J. Phys. B : At Mol. Opt. Phys. **48**, 224003 (2015).

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Accurate and efficient neutral pseudo-atom model to predict warm dense matter properties

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Modern applications of high-energy deposition on matter have allowed novel, ultra-fast, and non-equilibrium regimes of density and temperature to be accessed, which are of great theoretical, astrophysical and technological importance. Such regimes of warm-dense matter (WDM) are involved in inertial confinement fusion, Coulomb explosions, laser machining and ablation. The density can be of the solid order or higher while still having a temperature as high as few eV. These are strongly correlated systems where the coupling parameter Γ, that is the ratio of the Coulomb energy to the kinetic energy, exceeds unity.

Two important experimental techniques has been used to reach these extreme conditions : shock-compression [1] and isochorical heating [2]. In both case, a novel probing technique [3], namely the X-ray Thompson Scattering (XRTS), as distinguish itself as the key method to determine physical properties of WDM such as temperature, densities and mean ionisation. The differential cross section for XRTS is given by the total electron-electron dynamical structure factor (DSF) $S_{ee}(\mathbf{k},\omega)$. In order to extract physical properties, the experimental signal has to be fitted to theoretical calculations. Thus, a fast, accurate and efficient model is of great interest.

We propose to use the neutral pseudoatom (NPA) model, as given by Perrot and Dharma-wardana (PDW) [4,5] and adapted to the two-temperature [6], as an appropriate tool for this task. The objective of this presentation is therefold : i) to describe briefly the NPA model while illustrating its advantage over full molecular-dynamic density-functional-theory for the WDM regime and ii) to demonstrate its accuracy by presenting key quantities for two simple metals, namely Li and Al, in the shock-compressed system (electron density, ion structure factor) and in the isochorically-heated system (quasi-equilibrium pressure, phonon spectrum, ablation force).

References

1. L. B. Fletcher *et al*, Nature Photonics **9** (2015).
2. R. Ernforster *et al*, Science **323**, 1033, (2009).
3. S. H. Glenzer *et al*, Phys. Rev. Lett. **90**, 175002, (2003).
4. M. W. C. Dharma-wardana and F. Perrot, Phys. Rev. A **26**, 4 (1982)
5. F. Perrot, Phys. Rev. B **47**, 570 (1993).
6. L. Harbour, M. W. C. Dharma-wardana, D. D. Klug, L. Lewis, Contr. Plasma. Phys. vol. 55, 144-151 (2015)

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EFFICIENT CALCULATION OF ATOMIC RATE COEFFICIENTS IN DENSE PLASMAS

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Modelling electron statistics in a cold, dense plasma by the Fermi-Dirac distribution leads to complications in the calculations of atomic rate coefficients. The Pauli exclusion principle slows down the rate of collisions as electrons must find unoccupied quantum states and adds a further computational cost. Methods to calculate these coefficients by direct numerical integration with a high degree of parallelism are presented. This degree of optimization allows the effects of degeneracy to be incorporated into a time-dependent collisional-radiative model. Example results from such a model are presented.

References

1. V. Aslanyan, G. J. Tallents, Phys. Rev. E **91**, 063106 (2015).

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ATOMIC DATA AND PROCESSES. III

THE STARK-B DATABASE VAMDC NODE

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Accurate spectroscopic diagnostics and modeling require the knowledge of numerous collisional line profiles. The access to such data via an on line database is essential. The aim of STARK-B [1] is to meet these needs for widths and shifts of isolated lines of atoms and ions due to electron and ion impacts. It is devoted to modeling and spectroscopic diagnostics of stellar atmospheres and envelopes, laboratory plasmas, laser equipments and technological plasmas. So, the range of temperatures and densities covered by the tables is broad and depends on the ionization degree of the radiating atom

STARK-B is a collaborative project between the Astronomical Observatory of Belgrade (AOB) and the laboratory LERMA at Observatory of Paris, which started at the end of 2008. STARK-B is a database of the LERMA Paris Observatory and a node of VAMDC (Virtual Atomic and Molecular Data Centre) [2] [3] [4] [5] and thus complies with the standards of the Virtual Observatories.

This database opened at the end of 2008. Today, the database contains our calculated data for a varied number of transitions of more than 130 neutral or ionized atoms, published in international refereed journals. We continue to implement our published data, and the new ones as soon as they are published.

A summary of the scientific objectives, the key points of the impact-semiclassical-perturbation method used [6] for the calculations, the current state of development and our ongoing work and of our plans for the future objectives of the database will be presented on the poster. An example of the results of a query will also be displayed.

References

1. http://stark-b.obspm.fr
2. http://www.vamdc.eu
3. Dubernet, M. L., Boudon, V., Culhane, J. L., et al.: JQSRT, **111**, 2151 (2010)
4. Rixon,G., Dubernet,M.L., Piskunov,N., et al., in AIP Conf. Ser., 1344, eds. Bernotas A., Karazija R., & Rudzikas Z., 107 (2011)
5. M L Dubernet, B K Antony, Y A Ba, et al., J. Phys. B, 2016 *J. Phys. B: At. Mol. Opt. Phys.* **49** 074003 (2016)
6. Sahal-Bréchot, S. Dimitrijević, M.S., and Ben Nessib, N.: Atoms, **2(2)**, 225, doi:10.3390/atoms2020225 (2014)

ATOMIC DATA FOR TRANSITIONS IN S V

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In our recent papers [1-3] we have reported atomic data required in the interpretation of astrophysical and laboratory soft x-ray wavelength range. These calculations include levels energy, radiative decay rates, and photon and electron collision data. The present paper aims to systematically investigate the accuracy in the calculation of atomic data as energy levels, radiative decay rates, oscillator strengths, collision strengths and effective collision strengths for the particular case of Mg-like S ion.

We have carried out large close-coupling calculation using the multichannel *R*-matrix method [4] that includes extensive configuration interaction wavefunctions to represent the target states and which takes full account of resonance effect. The total (e^- + ion) wavefunction is expanded in terms of the 15 lowest eigenstates of S V, and each eigenstate is represented by a linear combination of single configuration functions, each of which has the same total LSπ symmetry as the target wavefunction. To construct these single configuration functions we employed eight orthogonal one-electron orbitals: $1s, 2s, 2p, 3s, 3p, 3d, 4s, 4p$ and four pseudo-orbitals: $\overline{4d}, \overline{4f}, \overline{5s}, \overline{5p}$. In order to form the (N+1) symmetries we consider all total angular momenta $0 \le L \le 15$, including both even and odd parities for doublet and quartet multiplicity.

The energy values and radiative decay rates have also been calculated using the SUPERSTRUCTURE program [5] and the Flexible Atomic Code (FAC) [6]. Both codes solve the scattering problem in the distorted wave approximation. The program SUPERSTRUCTURE uses radial wavefunctions calculated in a scaled Thomas-Fermi-Dirac statistical model potential. The scaling parameters were determined by minimizing the sum of the energies of all the tems, computed in LS-coupling, i.e., neglecting all relativistic effects. In relativistic configuration-interaction FAC calculation we included intercombination and magnetic quadrupole transitions from large scale valence-valence, valence -2p and valence-2s configurations. Total 96 configurations have been included in this calculation.

In order to assess the reliability of present results comparison with previously reported works [7,8] will be provided.

References

[1] K. Aggarwal, P.Bogdanovich, R. Karpuskiene, F.P.Keenan, R. Kiselius, V. Stancalie, ADNDT **107**, 140(2016).

[2] C.Iorga, V.Stancalie, Can. J. Phys.**93** , 1413(2015).

[3] V. Stancalie, Eur.Phys.J.D.**68**, 349(2014).

[4] P.G.Burke, K.A. Berrington, 1993 Atomic and Molecular Processes: An R-matrix Approach (Bristol: Institute of Physics Publishing)

[5] W. Eissner, Comput. Phys. Commun. **114**, 295(1998).

[6] M.F.Gu, Astrophys. J. **582,** 1241(2003).

[7] R. B. Christensen, D. W. Norcross, A. K. Pradhan, Phys. Rev. A **34(6)** (1986)

[8] L. Fernandez-Menchero, G. Del Zanna, and N. R. Badnell, A&A **572**, A115(2014)

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POSTERS: ATOMIC DATA AND PROCESSES

COLLISIONAL RADIATIVE MODEL TO STUDY ORGANIC LIBS PLASMA

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Laser Induced Breakdown Spectroscopy (LIBS) also called LIPS (Laser Induced Plasma Spectroscopy) is a technique for qualitative and quantitative elemental analysis of matter. The choice of an organic LIBS plasma was motivated by a large range of application, e.g. detection and identification of explosives, analysis of toxic metals in food products, or discrimination and identification of plastic waste.

A pulsed laser beam is focused onto the material to be analyzed creating a very hot plasma. When it cools, the plasma emits a spectrum characteristic of the composition of the material. The position of the lines in the obtained spectrum yields the elemental composition, while the intensity of these lines gives the quantitative information.

The aim of this work is a temperature and density diagnostic of an organic LIBS plasma. For this purpose we have developed a collisional-radiative model (CRM) that includes radiative and collisional excitation, radiative recombination, collisional ionization, three-body recombination, auto-ionization and dielectric recombination.

The CRM is a general formulation of atomic processes in plasmas. It can address many questions than cannot be treated within other models. Moreover, it is well suited for the description of a non local thermodynamic equilibrium (NLTE) plasma. The CRM also allows to quantify the magnitude of the deviation from LTE by calculating the ratio of non-equilibrium to equilibrium populations (factor b_i). It is possible, whatever the state of the plasma, to impose artificially ETL and compare the populations inferred with or without the imposition.

References

1. G. Travaillé et al., Spectrochim. Acta Part B, **64**, 931 (2009)
2. Grégoire et al., Spectrochim. Acta Part B, **31**, 74 (2012).

SEARCHING FOR DIELECTRONIC SATELLITE LINES ASSOCIATED WITH 3s→2p TRANSITIONS IN Fe XVII

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Dielectronic satellite emission has been shown to contribute to the L-shell x-ray spectra of highly charged iron. For example, essentially all n=3 to n=2 transitions of carbonlike, boronlike, berylliumlike, and lithiumlike iron situated in the 10.5 to 15.5 Å region blend with unresolved dielectronic satellite lines that involve a so-called spectator electron with a high principal quantum number $n \geq 4$ [1]. L-shell dielectronic satellite lines also have been shown to play a role in the case of Fe XVIII [2]. Moreover, Fe XVI lines with an n=4 spectator electron have been identified in the spectrum of the corona of the star Capella observed with the Chandra X-ray Observatory [3]. The Fe XVI dielectronic satellite lines in the Capella spectrum are close to the 3d→2p electric-dipole allowed transitions in Fe XVII, which are labeled 3C and 3D in standard notation. Using the Livermore electron beam ion trap facility we have recently identified these dielectronic satellite lines in the laboratory [4]. We have now extended our laboratory measurements to search for dielectronic satellite transitions associated with the three 3s → 2p transitions labeled 3F, 3G, and 3H, which are among the strongest lines in the Fe XVII spectrum. Surprisingly, we find that even the two strong electric dipole 3s → 2p transitions are not associated with any substantial amount of dielectronic satellite lines.

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References

1. M. F. Gu, S. M. Kahn, D. W. Savin, E. Behar, P. Beiersdorfer, G. V. Brown, D. A. Liedahl, and K. J. Reed, Astrophys. J., **563**, 462 (2001).

2. J. Clementson and P. Beiersdorfer, Astrophys. J., **763**, 54 (2013).

3. P. Beiersdorfer, M. F. Gu, J. K. Lepson, and P. Desai, in Astronomical Society of the Pacific Conference Series, Vol. 448, 16th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, ed. C. Johns-Krull, M. K. Browning, and A. A. West (San Francisco:Astronomical Society of the Pacific), 787 (2011).

4. P. Beiersdorfer et al., J. Phys. Conf. Proc. **583**, 012022 (2015).

ELECTRON-IMPACT EXCITATION AND RECOMBINATION OF MOLECULAR CATIONS IN COLD PLASMAS: APPLICATION TO H_2^+, BeH^+, CH^+, CO^+, N_2^+, AND BF^+

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The detailed collisional-radiative modeling of cold plasmas [1,2] requires accurate cross sections and rate coefficients of the major elementary processes, in particular ofthe dissociative recombination, ro-vibrational excitation and dissociative excitation [3]:

$$AB^+(N^+,v^+)+e^- \rightarrow A+B,\ \ AB^+(N^{+\prime},v^{+\prime}) + e^-,\ \ A+B^++e^-$$

Using the Multichannel Quantum Defect Theory (MQDT) [4], we have evaluated these data for a variety of ionized media.

For the fusion plasma edge, extensive cross sections and rate coefficients have been produced for HD^+, H_2^+, BeH^+ and CH^+.The CO^+[5]and N_2^+[4] reactive collisions with electrons have been investigated forthe plasma formed at the hypersonic entry of space-crafts in the Martian and Titan atmospheres respectively.We haverecently produced rate coefficients for BF^+, involved in the Plasma Ion Implantation technique [6].And finally, in order to model the cold environments involved in the chemistry of the early Universe, interstellar molecular clouds, supernovae and planetary atmospheres, rate coefficients for these electron-impact processes have been produced for HD^+, H_2^+ [7] CO^+ [5] and CH^+.

References

1. A. Bultel, invited lecture at this conference.
2. D. Reiter, invited lecture at this conference.
3. I. F. Schneider, O. Dulieu, J. Robert, editors, *Proceedings of DR2013: The 9th International Conference on Dissociative Recombination: Theory, Experiment and Applications, Paris, July 7-12, 2013,* EPJ Web of Conferences **84** (2015).
4. D. A. Little*et al*, *Phys. Rev. A***90**,052705(2014).
5. J. Zs. Mezei*et al*, *Plasma Sources Science and Technology***24**, 035005 (2015).
6. M. Maury, K. Hassouni, A. Michau, *Bull. APS***55** 7, CTP.00018(2010).
7. M. D. Epée Epée *et al*, *MNRAS***455**, 276 (2015).

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PLASMA EFFECTS ON ATOMIC DATA FOR THE K-VACANCY STATES OF HIGHLY CHARGED IRON IONS

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X-ray emission lines from accreting sources, most notably the K_α and K_β lines from iron ions, have observed widths and shifts which imply an origin very close to the compact object in many cases [1]. The inferred line origin can be near either the innermost stable circular orbit or the event horizon in the case of a black hole. The intensity of these lines can provide insight into the amount of gas and other properties, including the effects of special and general relativity in the emitting region, and this information is not available from other observational techniques.

Much of what we can learn from these K_α and K_β emission lines depends on the use of reliable atomic parameters that allow us to infer the rate at which ions emit or absorb in line transitions under various conditions. In the case of iron ions, for example, these atomic parameters allow us to derive the number of iron ions responsible for line emission observed from different objects, which in turn gives information on the fractional abundance of iron relative to other elements (i.e. hydrogen). However, the rates and assumptions employed in these model calculations are all based on isolated iron ions. They do not account for the true situation which is a dense plasma in which the effects of nearby ions and electrons can have significant effects on the processes affecting line emission and the survival or destruction of iron ions. Although dynamical models for black hole accretion flows appear to support the existence of rather high densities, up to $10^{20} – 10^{21}$ cm^{-3} [2,3], their effect on line emission has not been explored so far.

The main goal of the present work is to estimate the effects of plasma environement on the atomic parameters associated with the K-vacancy states in highly charged iron ions. In order to do this, multiconfiguration Dirac-Fock computations have been carried out for these ions by considering a time averaged Debye-Hückel potential for both the electron-nucleus and electron-electron interactions using a combination of the GRASP92 code [4] for obtaining the wavefunctions and the RATIP code [5] for computing the atomic parameters. A first set of results related to the ionization potentials, the K-thresholds, the transition energies and the radiative emission rates for some iron ions will be presented during the conference.

References

1. C.S. Reynolds and M.A. Nowak, Phys. Rep. **377**, 389 (2003).
2. R.C. Reis and J.M. Miller, Astrophys. J. **769**, L7 (2013).
3. J.D. Schnittman, J.H. Krolik and S.C. Noble, Astrophys. J. **769**, 156 (2013).
4. F.A. Parpia, C. Froese Fischer and I.P. Grant, Comput. Phys. Commun. **94**, 249 (1996).
5. S. Fritzsche, Comput. Phys. Commun. **183**, 1523 (2012).

RENORMALIZATION SHIELDING EFFECTS ON THE ELECTRON-IMPACT IONIZATION IN DENSE PLASMAS

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The influence of renormalization shielding on the electron-impact ionization process is investigated in dense partially ionized plasmas. The effective projectile-target interaction Hamiltonian and the semiclassical trajectory method are employed to obtain the transition amplitude as well as the ionization probability as functions of the impact parameter, the collision energy, and the renormalization parameter. It is found that the renormalization shielding effect suppresses the transition amplitude for the electron-impact ionization process in dense partially ionized plasmas. It is also found that the renormalization effect suppresses the differential ionization cross section in the peak impact parameter region. In addition, it is found that the influence of renormalization shielding on the ionization cross section decreases with an increase of the relative collision energy. The variations of the renormalization shielding effects on the electron-impact ionization cross section are also discussed.

Higher-order contribution in the resonant recombination of electron-ion interaction

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Resonant recombination plays a major role on the ionization equilibrium of plasmas [1] and yields strong spectral signatures used for their diagnostics. In the last decade, systematic calculations using state-of-the-art methods that included dielectronic recombination (DR) have significantly improved the quality of ionization equilibrium data sets extensively used by the astronomical community [2]. Beyond DR, resonant recombination involves not so well studied processes due to higher-order (HO) correlations, in which two or even three bound electrons can be simultaneously excited by the resonantly captured electron: trielectronic and quadruelectronic recombination (TR and QR). Using an electron beam ion trap, Beilmann and co-authors [3-5] resolved the contributions of such HO processes in the K-L intershell recombination, and found them to be strong and in some cases even dominant relatively to the corresponding DR strengths. In available DR data these HO channels have been included implicitly, and it is difficult to disentangle TR and/or QR from DR channels by codes.

Here we make a detailed theoretical investigation of HO contributions for carbon-like iron ions, including L-L plus L-M, K-L intershell and intrashell resonant recombination channels, and find that they are only partially included in published Maxwellian-averaged DR rate coefficients. We develop a decomposition procedure and apply it to carbon-like iron ion, thereby finding for L-L intrashell plus L-M intershell HO processes contributing up to 40% in the photoionized plasma zone (at temperatures of 20–70 eV). These HO channels have already been indirectly included in previous works. We found that they contribute ∼25% of the total radiative energy loss of the resonant recombination at the temperature with peak radiative loss. As for the K-L intershell contributions, which typically have not been included in earlier calculations, where HO contribution to the total K-L resonant recombination rates is about 35-40%. Their cooling effect is enhanced ($\gtrsim$6%) relative to that of L-L plus L-M processes at T$\gtrsim$ 2 keV for collisionally heated plasmas.

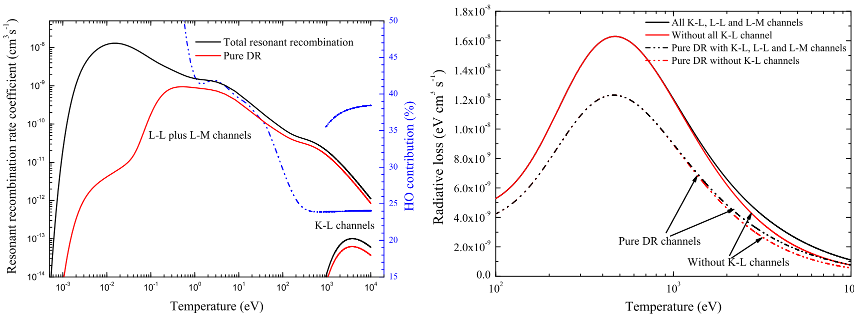

Figure 1. Recombination rate coefficients with and without HO contribution, and radiative energy loss.

References

1. N.R. Badnell, *J. Phys. B: At. Mol. Opt. Phys.* **39**, 4825 (2006).
2. P. Bryans, N.R. Badnell, T.W. Gorczyca, *et al.*, *Astrophys. J. Supp. Ser.* **167** 343 (2006)
3. C. Beilmann, P.H. Mokler, S. Bernitt, *et al.*, *Phys. Rev. Lett.* **107** 143201 (2011)
4. C. Beilmann, Z. Harman, P.H. Mokler, *et al.*, *Phys. Rev. A* **88** 062706 (2013)
5. T.M. Baumann, Z. Harman, J. Stark, *et al.*, *Phys. Rev. A* **90** 052704 (2014)

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Analysis of the VUV emission spectrum of the Er^{3+} ion (Er IV)

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The lanthanide ions provide a wealth of applications in astrophysical plasmas diagnostics, in solid-state laser materials and in lighting industries. They also bear fundamental interest for the theory of atomic structure applied to f^N configurations [1 and ref. therein]. We have completed publications reporting wavelengths, energy levels and semi-empirically computed transition probabilities for several moderately charged ions Nd IV [2], Nd V [3,4], Tm IV [5], Eu III [6] and Yb V [7].

The present work concerns the Er IV spectrum. Theoretical predictions of level energies and transition probabilities in Er^{3+} obtained by using Cowan's codes [8] showed that early results from W.J. Carter [9] needed major revision. New erbium high resolution emission spectra have been recorded using vacuum spark sources and the 10.7-meter normal incidence vuv spectrograph at the Meudon Observatory. Their analysis led to the identification of about 590 spectral lines in the wavelength region of (851Å – 2277Å) and the determination of 120 energy levels belonging to the $4f^{11}$, $4f^{10}5d$, $4f^{10}6s$, $4f^{10}6p$ configurations, above the ground level $4f^{11}\ {}^4I_{15/2}$. Parametric studies of the configurations provided level compositions in intermediate coupling scheme.

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References

1. J.-F. Wyart, A. Meftah, J. Sinzelle, W.-Ü L. Tchang-Brillet, N. Spector and B. R Judd, J. Phys. B: At. Mol. Opt. Phys. **41**, 085001 (2008)
2. J.-F. Wyart, A. Meftah, W.-Ü L. Tchang-Brillet, N. Champion, O. Lamrous, N. Spector and J. Sugar, J. Phys. B: At. Mol. Opt. Phys. **40**, 3957-3972 (2007)
3. A. Meftah, J.-F. Wyart, J. Sinzelle, W.-Ü L. Tchang-Brillet, N. Champion, N. Spector and J. Sugar, Physica Scripta **77**, 055302 (2008)
4. D. Deghiche, A. Meftah**,** J.-F. Wyart, N. Champion, C. Blaess, W.-Ü L. Tchang-Brillet, Physica Scripta **90**, 095402 (2015)
5. A. Meftah, J.-F. Wyart, N. Champion and W.-Ü L. Tchang-Brillet, European Physical Journal D **44**, 35-45 (2007)
6. J.-F. Wyart, W.-Ü L. Tchang-Brillet, S. S. Churilov and A. N. Ryabtsev Astronomy & Astrophysics 483, 339-359 (2008), *VizieR Online Data Catalog*, 348:30339-+.
7. Meftah, A.; Wyart, J.-F.; Tchang-Brillet, W.-Ü L.; Blaess, Ch.; Champion, N., *Phys.Scr.* **2013**, *88*, 045305 (12pp)
8. R.D. Cowan, *The Theory of Atomic Structure and Spectra* (U. California Press, Berkeley, CA, 1981).
9. W.J. Carter, Thesis, Johns Hopkins Univ. 1966.

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Revised and extended analysis of trebly ionized selenium: Se IV

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Abstract:

We report revised and extended measurements of trebly ionized selenium, an element of the iron group detected in nearly twice as many planetary nebulae as any other trans-iron element. We use. The fourth spectrum of selenium has been investigated in the wavelength region 300-2080Å using triggered spark source The ground configuration of Se IV is $4s^2 4p$ and its outer excitation is basically one-electron system with doublet structure while inner excitation leads to a three-electron system making structure more complex. We have studied the $4s^2np(n=4-7)+4s^2nf(n=4-6)+4p^3+4s4p(5s+6s+4d+5d)$ configurations in the odd parity system and $4s^2ns(n=5-7)+4s^25g$ configurations in the even parity matrix. In one electron spectrum, the levels of $4s^2$(5s,6s,4p,5p,6p,4d,5d,4f and 5g) configurations are being confirmed but revised the levels of $4s^2$(7s,7p,6d and 5f) configurations. In three-electron system, $4s4p^2\ ^4S_{3/2}$ and all levels of $4p^3$ configuration have been revised. The 4s4p(4d+5d+5s+6s) configurations have been studied for the first time. The analysis is being revised and extended with the help of semi-empirical quasi-relativistic Hartree-Fock calculations. A complete interpretation of the level system for both parities will be assisted by least squares fitted parametric calculations. Forty-six odd and seventeen even parity energy levels are now known based on the identification of three-hundred transitions. The Ionization limit is found to be $346721 \pm 265 cm^{-1}$(42.988 ± 0.033eV).

K-SHELL SPECTROSCOPY IN HOT PLASMAS: STARK EFFECT, BREIT INTERACTION AND QED CORRECTIONS

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In hot dense plasmas encountered for instance in inertial confinement fusion, the line broadening resulting from Stark effect can be used as a diagnostics of electronic temperature and density. The capability of the detailed opacity code SCO-RCG [1], as concerns K-shell spectroscopy, was recently improved following an approach proposed by Gilles and Peyrusse [2] for the modeling of Stark effect in hydrogen- and helium-like ions. Neglecting non-diagonal terms in dipolar and collision operators, the line profile can be written as a sum of Voigt functions associated to the Stark components. The lines $Ly_{\alpha,\beta,\gamma,\ldots}$ are obtained from the well-known description of H-like ions in parabolic coordinates within SO(4) symmetry. Relativistic fine-structure of the Lyman lines is included by diagonalizing the Hamiltonian matrix associated to quantum states having the same principal quantum number. For the lines of He-like ions, the direct singlet-triplet mixing is neglected and for He_α, both the resonance and intercombination ($1s2p\ ^3P$ - $1s^2$) lines are taken into account. It is possible, in SCO-RCG, to test different micro-field distributions (depending on the ionic coupling parameter and the electronic screening constant) obtained for instance from a combination of the APEX (Adjustable Parameter EXponential) method with Monte Carlo simulations [3]. The code enables one to study the decoupling between T_e and T_i or the role of satellite lines (such as Li-like $1sn\ell n\ell' \rightarrow 1s^2 n\ell$ lines). Comparisons with Stark profiles resulting from simpler and widely-used semi-empirical models will be presented. In addition, we propose analytical formulas, obtained from fitting the results of Multi-Configuration Dirac-Fock (MCDF) calculations [4], for the contribution of Breit interaction to the energies of the levels of configurations $1s^2$, 1s2s, 1s2p, 1s3s and 1s3p for He-like ions. Since they are important for high-precision spectroscopy [5-7], QED corrections (self-energy, vacuum polarization), as well as nuclear finite size, nuclear mass and radiative-recoil effects are included. We discuss the generalization of Bethe logarithms [8] and the sensitivity of the self-energy of two and three-electron atoms with respect to the calculation of the effective charge, for instance comparing of the mean radius of the Dirac-Fock orbital with the relativistic hydrogenic one, using relativistic screening constants [9] or within the Welton approach of the Lamb shift [10,11].

References

[1] J.-C. Pain, and F. Gilleron, High Energy Density Phys **15**, 30 (2015).
[2] D. Gilles and O. Peyrusse, J. Quant. Spectrosc. Radiat. Transfer **53**, 647 (1995).
[3] A.Y. Potekhin, G. Chabrier and D. Gilles, Phys. Rev. E **65**, 036412 (2002).
[4] J. Bruneau, J. Phys. B: At. Mol. Phys. **16**, 4135 (1983).
[5] E. Aglitski, unpublished results (http://nlte.nist.gov/NLTE9).
[6] O. Marchuk, "Modeling of He-like spectra measured at the tokamaks TEXTOR and TORE SUPRA", PhD Thesis (Ruhr Universität Bochum, 2014).
[7] A.N. Artemyev et al., Phys. Rev. A **71**, 062104 (2005).
[8] G.W.F. Drake and R.A. Swainson, Phys. Rev. A **41**, 1243 (1990).
[9] F. Lanzini and H.O. Di Rocco, High Energy Density Phys. **17**, 240 (2015).
[10] T.A. Welton. Phys. Rev. **74**, 1157 (1948).
[11] P. Indelicato, O. Gorceix and J.-P. Desclaux, J. Phys. B: At. Mol. Phys. **20**, 651 (1988).

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PLASMA DIAGNOSTICS WITH EUV SPECTRA FROM HIGHLY CHARGED IONS OF YTTRIUM

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Extreme-ultraviolet spectra of the L-shell ions of highly-charged yttrium (Y^{29+}-Y^{36+}) were observed in the electron beam ion trap (EBIT) at the National Institute of Standards and Technology [1] using a flat-field grazing-incidence spectrometer [2] in the wavelength range of about 4 nm to 20 nm. Neon, xenon, iron and oxygen lines [3] were used for the wavelength calibration. Detailed collisional-radiative (CR) modeling [4] for the non-Maxwellian EBIT plasma was used to simulate the spectra and classify previously unknown lines. Among the 63 newly identified yttrium lines measured with uncertainties between 0.001 nm and 0.003 nm, several lines are due to the forbidden magnetic dipole (M1) transitions within $2p^n$ configurations. To analyze the potential applicability of these lines to plasma diagnostics, we performed large-scale CR calculations of yttrium spectra in Maxwellian plasmas with electron temperatures on the order of several keV; such high temperatures correspond to the maximal abundance of the L-shell ions of yttrium. It was found that several line ratios show strong dependence on electron density and/or electron temperature and hence may be implemented in diagnostics of hot plasmas and, in particular, fusion devices.

References

1. J. D. Gillaspy, Phys. Scr. T **71**, 99 (1997).
2. B. Blagojevic et al., Rev. Sci. Instrum.**76**, 083102 (2005).
3. Yu. Ralchenko, A. Kramida, J. Reader, and the NIST ASD Team, NIST Atomic Spectra Database (version 5), http://physics.nist.gov/asd.
4. Yu. Ralchenko and Y. Maron, J. Quant. Spectosc. Radiat. Transfer **71**, 609 (2001).

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ELECTRON-IMPACT EXCITATION AND IONIZATION CALCULATIONS FOR TUNGSTEN AND MOLYBDENUM IONS

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Neutral tungsten (W) and molybdenum (Mo) are of continued interest within the magnetically-confined plasma community as potential candidates for plasma facing components, due to their high melting points and thermal conductivity. In fact, the Massachusetts Institute of Technology's Alcator C-Mod tokamak already employs a molybdenum lining [1], and it is now certain that ITER will use tungsten as the plasma facing material in the divertor region [2]. Although these metals are chosen to withstand the high temperatures within a reactor, loss of plasma energy due to sputtering and radiation still needs to be . Therefore comprehensive data sets are required for all collisional processes, including excitation, ionization and recombination. Our focus shall be the near-neutral stages of tungsten and molybdenum for which the R-matrix with pseudo-states (RMPS) [3,4] is well suited.

The motivation for our molybdenum study is the works of Badnell et. al [5] and Kwon et. al. [6]. The comparison of the results saw almost a factor of three difference in the total ionization cross sections. It is well-known that for neutral systems, perturbative methods such as the distorted-wave approximation overestimate the ionization cross section. We shall explore the differences between these earlier results and our present RMPS study.

Fundamentally, for highly charged states of tungsten, our work has included the calculation of energy levels, transition probabilities, collision strengths and Maxwellian averaged effective collisions strengths for the W LXIV ion. These were carried out using both semi-relativistic methods (where relativistic effects are approximated using the Breit-Pauli Hamiltonian) and fully-relativistic methods. Surprisingly good agreement was found between the two sets of data, which is important as it extends the capability of the R-matrix ICFT method [7] which is less computationally demanding than either Breit-Pauli or DARC R-matrix.

References

1. Ascoli-Bartoli, U., et al., in Plasma Physics and Controlled Nuclear Fusion Research 1974 (Proc. 5th Int. Conf. Tokyo, 1974), **1**, IAEA, Vienna, Austria (1975) 191.
2. Pitts R. A., Carpentier S., Escourbiac F., Hirai T., Komarov V., et. al., J. Nucl. Mater., **438**, S48-S56 (2013).
3. Badnell N. R. and Gorczyca T. W., J. Phys. B: At. Mol. Opt. Phys., **30** 3897-3911.
4. Ballance C. P. and Griffin D. C., J. Phys. B: At. Mol. Opt. Phys., **39** 3617-3628.
5. Badnell N. R., Gorczyca T. W., Pindzola M. S. and Summers H. P., J. Phys. B: At. Mol. Opt. Phys., **29**, 3683 (1996)
6. Duck-Hee Kwon, Yong-Joo Rhee, yong-Ki Kim, Int. J. Mass Spectrom., **245**, 26-35 (2005).
7. Griffin D. C., Badnell N. R. and Pindzola M. S., J. Phys. B: At. Mol. Opt. Phys., **31**, 3713-3727 (1998).

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EBIT SPECTROSCOPY OF HIGHLY CHARGED TIN IONS FOR EUV SOURCE DIAGNOSTICS

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Charge-state-resolved spectra of SnIX-XV ions in the optical and EUV domain were simultaneously obtained using the electron beam ion traps (EBIT) at the Max Planck Institute for Nuclear Physics. The tuneable electron beam energy of the EBIT enabled us to obtain the energy dependence of the fluorescence intensity of spectral lines and, thus, to assign them to their respective charge states. These findings are of particular relevance to extreme ultra-violet (EUV) light sources and the diagnostics thereof.

POSTERS: LOW TEMPERATURE PLASMAS

A monitoring method of chamber wall conditions using outgassing in He plasma

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Wall conditions of plasma reactor have an important role in plasma process. The change in the wall conditions affect the radical state in the plasma, leading to the first wafer effect, the process drift issue and the defect problem. Since various by-products are deposited on the wall during the process, in situ dry-cleaning is necessary after the plasma process to maintain the wall conditions. For the dry-cleaning, NF_3 and O_2 plasmas are generally used to remove the silicon and carbon by-products from the wall.

Recently, hydro-fluorocarbon gases such as CHF_3 CH_2F_2 and CH_3F are widely used in plasma etching process for high selectivity and profile control. These gases deposit the carbon polymer layer not only on the wafer surface but on the chamber wall. Therefore, the in situ dry cleaning with O_2 plasma should be performed to remove the carbon polymer. At this moment, H contained in the carbon polymer can react with O radical supplied from the O2 plasma to form H_2O that stays on the chamber wall for a long time [1]. This H_2O may damage to the anodized chamber wall when F-contained process gases are used in the process [2], and cause the first wafer effect after a long idle time of the chamber and the residue defect on the water. Thus, the method to control of H on the wall is needed in the hydro-fluorocarbon plasma process.

In this paper, we investigated the plasma treatment effect with various gases on H level on the wall. However, there have been few methods to analyse wall conditions without breaking the vacuum state. In order to analyse wall conditions in vacuum state, a He plasma monitoring method was suggested. In the He plasma, a small amount gases outgassed from the chamber wall could be detected by the optical emission spectroscopy, representing the chamber conditions. Just after the O_2 dry-cleaning, H and OH were detected in the He plasma, meaning that the H_2O remained on the chamber wall. The Ar plasma treatment after O_2 dry-cleaning, in which the sputtering effect by Ar ions was expected, had little effect to remove the H_2O from the chamber wall. The NF_3 plasma treatment reduced the remained H_2O but the chamber wall was strongly terminated by F. The N_2 plasma treatment was effect to reduce the H_2O and maintain steady chamber wall conditions.

References

1. A. K. Srivastava, T. Ohashi and V. M. Donnelly, J. Vac. Sci. Technol. A **33**, 041301 (2015)
2. N. Ito, T. Moriya, F. Uesugi, M. Matsumoto, S. Liu andY. Kitayama, Jpn. J. Appl. Phys., **47**, 3630 (2008).

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INVESTIGATION ON THE ROLE OF THE BLOCKING CAPACITOR IN SINGLE AND DUAL CCRF DISCHARGE

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The influence of the blocking capacitor on capacitively coupled radio frequency plasma in a symmetric geometry are investigated using a two-dimensional particle-in-cell coupled with Monte Carlo collision model. RF voltage is applied through a blocking capacitor C_B which is brought into the circuit between the radio-frequency generator and the powered electrode. The working gas used is argon, our simulations are performed using a bounded electrostatic PIC-MCC code (XPDP2) in 2D (x, y) configuration space and 3D (V_x, V_y, V_z) velocity space along. The elastic scattering, excitation and ionization are included in our model for electron-neutral and ion-neutral collisions. Our simulations were performed with electrode spacing $3\ cm$, parameter values such as the blocking capacitor and voltage amplitude are used and the pressure chamber is $5\ mTorr$. The secondary electron emission coefficient for argon ions was 0.2. The simulation area is uniformly divided into 200 cells along the X-axis and 600 cells along the Y-axis. In order to resolve the RF cycle of both frequencies, the fundamental time step is chosen as $dt = 3.60.10^{-11}s$. In each case we used about 150 macro-particles per cell. The initial electron and ion temperatures are $3\ eV$ and $0.026\ eV$, respectively. All the presented results in this paper are averaged over one RF period. The external circuit used consists of an ideal voltage source in series with a blocking capacitor that represents the dc self-bias.

$$V_{RF} = V_c(t) + V_{sp}(t) + V_{bulk}(t) + V_{sg}(t) \qquad (1)$$

Special attention is focused on the electrical asymmetry behavior of the discharge in the case of single $(13, 56\ MHz)$ or the dual frequency $(13, 56$ and $27, 12\ MHz)$ coupled with the fixed blocking capacitor values. The results such as densities profiles, ion energy distributions and the symmetry parameter are discussed. A significant electrical asymmetry is observed for a dual frequency at low values of C_B . The electrical asymmetry effect is no longer dependent on the frequency at high values of C_B . However the shape of the IED is directly related to radio frequency signal $(1f$ or $2f)$.

References

1. V. Vahedi, C.K. Birdsall, M.A. Lieberman, G. DiPeso, and T.D. Rognlien. Phys. Fluids **B 5 (7)** 2719-2729 (1993).
2. V. Vahedi and G DiPeso. J. Comp. Phys. **131**, 149-163 (1997).
3. E Schungel *et al* . J. Appl. Phys.**112** 053302 (2012).
4. Z Donkó, J Schulze, U Czarnetski and D Luggenholscher. Appl. Phys. Lett. **94** 131501 (2009).
5. J Schulze, E Schngel, Z Donkó and U Czarnetski. J. Phys. D: Appl. Phys. **43** 225201 (2010).
6. J Schulze *et al* . Appl. Phys. Lett. **98** 031501 (2011).
7. Yu. P. Raizer and M.N Shneider. Plasma Sources Sci. Technol. **1** 102-108 (1992).
8. U. Czarnetski, J Schulze, E Schngel, and Z Donkó. Plasma Sources Sci. Technol.**20** 024010 (2011).
9. J Schulze, E Schungel, U Czarnetzki and Z Donko. J. Appl. Phys. **106** 063307 (2009).
10. A Perret, P Chabert, J Jolly and J.P Booth. Appl. Phys. Lett. **86** 021501 (2005).
11. M.A Lieberman, J.P Booth, P Chabert, J.M Rax and M.M Turner M.M. Plasma Sources Science and Technology, **11** 283 (2002)

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ARGON METASTABLE DENSITY IN AN ATMOSPHERIC MICROPLASMA JET IN INTERACTION WITH A DIELECTRIC SURFACE

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There has been a growing interest in the study of low-temperature atmospheric-pressure micro-plasma jets (APMPJs) sustained in rare gases and propagating in ambient air due to their attractiveness for various applications. Because of their capability to generate highly reactive species, APMPJs are ideal for biomedical and surface applications. Previous studies showed that argon APMPJs propagating in ambient air are filamentary [1]. Recently, stable and more homogenous argon APMPJs in interaction with a dielectric surface have been developed and studied using fast imaging [2]. The homogenous discharge is obtained when the dielectric surface is placed at about 5 mm from the APMPJ nozzle. Knowledge of the active species produced in APMPJs and their interaction with the surface is of great importance for the above-mentioned applications.

Here, we report space- and time-resolved argon metastable absolute densities, $Ar(3P_2)$, generated by a APMPJ operated in argon and in interaction with a quartz dielectric surface, and determined by tunable diode laser absorption spectroscopy. The spatio-temporal distribution of the $Ar(3P_2)$ density is presented and discussed under various operating conditions of the plasma jet. The employed setup of the argon APMPJ is similar to that previously used for helium metastable density measurements [3]. To sustain the argon APMPJ, a high positive voltage pulse (4.5–6 kV) is applied at a repetition frequency of 20 kHz. The full width at half maximum of the applied voltage pulse is 250 ns at maximum amplitude of 6 kV. A glass plate is placed at 5 mm from the APMPJs nozzle, perpendicularly to the trajectory of the argon APMPJ, allowing the creation of diffuse plasma.

The $Ar(^3P_2)$ absolute density is measured using laser absorption spectroscopy to probe the transition at 811.531 nm. The results reveal a sensitive dependence on the gas flow rate as well as on the axial and radial position, with a maximum density in order of 6×10^{13} cm^{-3}, obtained near the surface.

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References

1. B. Niermann et al. Plasma Sources Sci. Technol. **21**, 034002 (2012).
2. G. Bauville et al., 22nd International Symposium on Plasma Chemistry (ISPC22), Anvers, Belgique (5-10 juillet 2015). Proceedings P-II-4-9.
3. G. Cadot et al., IEEE Trans. Plasma Sci. **42**, 2446 (2014).

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MEASUREMENT OF AXIAL ION FLOW PROFILES IN A LINEAR HELICON PLASMA WITHOUT EXPLICIT DE-CONVOLUTION OF THE MEASURED LINE SHAPES

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The task of obtaining ion flow velocities in a magnetized plasma using laser induced fluorescence (LIF) is often complicated by necessitating de-convolution of the measured LIF spectra with respect to the quantum-mechanical structure of the energy levels employed. Hence, precise knowledge of the strength of the local magnetic field and the resulting line structure is a demanding requirement. To overcome this, we show in this work a simplified method for measuring the ion velocity by leveraging the symmetry of the σ^+ and σ^- lines of the Zeeman effect. Laser induced fluorescence was employed to pump the $3d^4F_{7/2} \rightarrow 4p^4D^\circ_{5/2}$ transition in singly ionized argon in a linear helicon plasma. By polarizing the incident laser light to excite the σ^+ and σ^- transitions independently and measuring the fluorescence response, the Doppler shift is measured by taking the midpoint between the σ^+ and σ^- groupings. A traditional de-convolution procedure accounting for natural line width, Zeeman splittings, and Doppler broadening was used as a benchmark. Ion velocities measured using this new method are compared with the de-convolved benchmark and a fair agreement between both methods is seen. This comparison also allows assessing the impact of the Zeeman splitting of the degenerate energy states on the actual measured line width for measurement of the ion temperature T_i. We show a significant impact on the order of 10% when T_i is evaluated based on a pure Gaussian width of the measured LIF profile compared to accounting for the line shape effects from the Zeeman components.

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METASTABLE INFLUENCE ON THE COLLISIONAL-RADIATIVE KINETICS OF A HE-NE DISCHARGE

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Metastable states can have a significant influence on the kinetics of a non-equilibrium discharge plasma. In a helium-neon discharge this influence is reinforce due to the quasi-resonance in energy existing between the two metastable states of He and several excited states of Ne. We have investigated this influence for a plasma created inside a positive column of low pressure (few mbar) He-Ne dc discharge, at moderate current (≈ 15 mA/cm^2). At this parameter range, the main processes for determining the populations of atomic excited states are electronic collisions, radiative decay, resonance collisions with metastable states and diffusion. To analyse the kinetic of these processes, a 1D collisional-radiative (1D-CR) model have been developed and implemented in a numerical code taking full account of the radiative transfer of the resonance lines, which play an important role [1]. As input of the 1D-CR model, the electron density profile as well as the energy distribution function of the electrons (EDFE) have been determined from a 1D plasma discharge model similar to the one detailed in [2,3]. In this model, the electrons and ions are described through a 1D radial fluid equation derived from the Boltzmann equation with the two-terms approximation for the electrons. The ions are considered as a cold fluid, whereas the macroscopic properties of the electron fluid at a given point are determined by solving the homogeneous Boltzmann equation using the local mean electron energy approximation.

In order to validate our theoretical model, experimental spectra of the emitted lines in the transverse and longitudinal directions, between 300 and 1000 nm have been recorded. A significant part of these lines concern transitions down to metastable states of He and Ne. For these lines comparison between longitudinal and transverse spectra allows for a direct measurement of metastable populations through self-absorption. The metastable populations can be quite sensitive to the presence of impurities. In our experimental setup, impurities are kept at a very low level as demonstrated by our experimental spectra. Therefore an accurate comparison between theoretical predictions and experimental results can be performed using a unique set of atomic data, both in the plasma discharge model and in the 1D-CR one. These results will be presented at the conference. We will present also results concerning the influence of boundary conditions on the density of the metastable populations and a quantitative estimate of the impact of two step ionization processes on the EDFE and on the kinetics of the ionized gaz.

References

1. J.S. Macé, G. Maynard and A. Virdis, Plasma Sources Sci. & Technol. 23, 045013 (2014)
2. L.L. Alves, Plasma Sources Sci. & Technol. 16, 557 (2007)
3. L.L. Alves, G. Gousset, C.M. Ferreira, Phys. Rev. E 55, 890 (1997)

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CH_4-CO_2 REFORMING IN SURFACE-DISCHARGE REACTOR CONTAINING ZnO-CuO/Al_2O_3 CATALYSTS. INFLUENCE OF THE RATIO ZnO/CuO ON PRODUCTS DISTRIBUTION.

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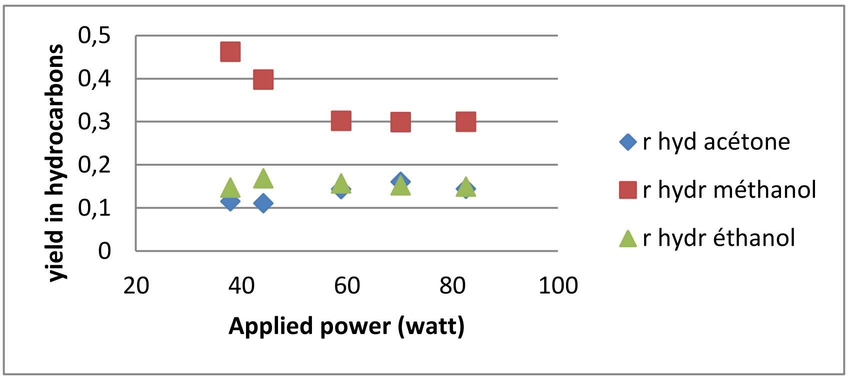
Dry reforming of methane (CH_4) is carried out in an atmospheric pressure Dielectric Barrier Discharge (DBD) reactor. The two aluminum electrodes of 3 mm in thickness are separated by a 3 mm thickness dielectric sheet made of quartz. Each electrode present 3 branches and the space between two adjacent branches is filled with alumina beads of 2 mm diameter coated with ZnO-CuO catalysts. AC voltage 30 kHz is applied on the electrodes. The feedstock is a mixture of argon, carbon dioxide and methane with 40 mL/min flow rate of each gas. At the reactor outlet, the gas goes through a condenser at 4 °C in order to condense the liquid products. The reforming reaction products are identified by gas chromatography. The effect of the applied power and the ratio of ZnO/CuO on the product distribution are studied. The catalyst coating of alumina beads is performed by a new technique named Fluidized Spray Plasma .In these technique thin layers of ZnO-CuO have been produced on the surface of alumina beads by reaction of nitrates precursor with reactive low pressure plasma. The characteristics of these catalysts have been determined by SEM, Raman and ICP analysis.

The conversion rates, around 50% and 30% were achieved respectively for CH_4 and CO_2[1] with a yield in the hydrocarbon for methanol around 45%. The conversion rates of both compounds depend strictly on the applied power while the nature of the catalysts modifies the distribution of products. This study demonstrated that more than 9 liquid hydrocarbons are formed during the dry reforming of methane at around the room temperature. The major liquid products are methanol, ethanol and acetone. Whatever the catalyst, the conversion rate of CH_4 and CO_2 increases with the applied power whiles the selectivity of gas products dependents on the applied power. The condensed liquids collected under our experimental conditions, such as ethanol or methanol, represent more than 10% wt of the products.



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[1] M. Nikravech, A. Rahmani. C. Lazzaroni and K. Baba, 22nd International Symposium on Plasma Chemistry 2015 (ISPC 22, P-II-8-32), http://www.ispcconference.org/ispcproc/ispc22/P-II-8-32.pdf

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EXPERIMENTAL AND THEORETICAL PLASMA EMISSION SPECTRA OF ATOMIC AND MOLECULAR GASES IN THE UV/VIS REGION EXCITED BY INTENSE EUV PULSES

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We carried out experimental measurements of photoionized plasma emission spectra in the ultraviolet and visible light (UV/Vis) wavelength ranges for noble and molecular gases. The photoionized plasmas were created using high-intense laser produced plasma extreme ultraviolet (EUV) source. The source was based on gas-puff target [1,2] irradiated with 1-10ns/5.6-6J/10Hz Nd:YAG laser systems. The EUV radiation pulses were collected and focused using multifoil EUV collector. The laser pulses were focused on a gas stream, injected into a vacuum chamber synchronously with the EUV pulses. Irradiation of gases resulted in formation of low temperature photoionized plasmas emitting radiation in the UV/Vis spectral ranges (200-780 nm). Photoionized plasmas produced this way consisted of atomic and molecular ions with various ionization states. Mostly observed and identified spectral lines originated from radiative transitions in singly and doubly charged ions or atoms. In parallel, an atomic multiplet code based on Cowan's program [3] has been employed to perform the theoretical emission spectra. We compare the calculated spectrum lines for a few selected ions with experimentally obtained results.

References

1. A. Bartnik et al. Nucl. Inst. Meth. A **647** (2011) 125
2. A. Bartnik et al. Laser & Particle Beams **31** (2013) 195–201
3. R. D. Cowan, The Theory of Atomic Structure and Spectra. University of California Press, 1981.

POSTERS: HIGH ENERGY DENSITY PLASMAS

Analysis of X-ray spectra measured on the PHELIX laser facility

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We present a new LTE atomic code based on the MCDF (Multi-Configuration Dirac Fock) approach [1] for the interpretation of x-ray spectra. The configurations are obtained from fluctuations around a relativistic average atom and selectedaccording to criteria on theirprobability estimated as a binomial distribution of thepopulations of the electronic subshells [2]. Configuration interaction in non-relativistic configuration is taken into account. The transition arrays for which the number of lines is too large are described in the UTA (Unresolved Transition Arrays) formalism in jj-coupling, relying on an efficient direct computation of the two-electron relativistic energy variance and shift for electric and magnetic transitions of general multipole order [3]. This code is used to interpret the x-ray emission spectra of copper (Z=29), germanium (Z=32), rubidium (Z=37) and gold (Z=79) measured on the Phelix laser at GSI in 2013 [4]in order to determine the maximum charge state reached in the plasma.The measurement was performed in the 1.7-3.25 keV energy range at a laser intensity of $6x10^{14}$ W/cm^2.Results are compared to the ones from the SCO-RCG code [5] and NLTE effects are investigated.

References

[1] J. Bruneau, J. Phys. B: At. Mol. Phys. **16**, 4135 (1983).
[2] M. Comet et al., Phys. Rev. C **92**, 054609 (2015).
[3] M. Krief and A. Feigel, High Energy Density Phys. **17**, 254 (2015).
[4] D. Denis-Petit et al., J. Quant. Spectrosc. Radiat. Transfer 148, 70 (2014).
[5] J.-C. Pain and F. Gilleron, High Energy Density Phys. **15**, 30 (2015).

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TIME-RESOLVED SPECTROSCOPY DIAGNOSIS AND ENERGY BALANCE OF IMPLOSION CORES IN OMEGA EXPERIMENTS DRIVEN BY SHAPED LASER PULSES

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Time-resolved spectroscopy diagnosis of core conditions in OMEGA implosions driven by shaped laser pulses –including low- and high-adiabat shaping pulses-- has been performed. The method relies on the observation and analysis of argon K-shell x-ray line spectra from argon-doped deuterium-filled plastic-shell targets recorded with time-integrated and streaked crystal spectrometers. The argon line spectrum is primarily emitted during the deceleration and stagnation of the implosion thus providing a spectroscopic signature of the state of the burning plasma. The observed spectra include parent and satellite line transitions in H-, He- and Li-like Ar ions thus covering a broad photon energy range from 3500eV to 4300eV with a spectral resolution power of approximately 500. The experimental spectra are analyzed with a detailed spectroscopic model that takes into account collisional-radiative atomic kinetics, Stark-broadened line shapes including the ion dynamics effect, and spectroscopic quality radiation transport [1,2]. Extracted temperature and density time-histories are representative of the state of the core plasma during fuel burning [3,4]. The results provide experimental evidence of how several shaped laser pulses produce implosions with different hydrodynamic characteristics. Furthermore, a thermodynamic and energy balance analysis of the implosion core based on the spectroscopic results is made and comparisons with 1D hydrodynamic simulations are also discussed. The present methodology opens up a window into implosion core dynamics and permits an assessment of the energy exchange between the core and the un-ablated, compressed shell confining the core.

This work is sponsored in part by DOE NLUF Grant DE-NA0002267, and LLNL. R. Florido is grateful for support from EUROfusion Consortium, Task Agreement WPENR *Enabling Research IFE*, Project AWP15-ENR-01/CEA-02.

References

1. R. Florido, T. Nagayama, R. C. Mancini, R. Tommasini, J. A. Delettrez, S. P. Regan, V. A. Smalyuk, R. Rodríguez and J. M. Gil, Rev. Sci. Instrum. **79**, 10E310 (2008).
2. R. Florido, R. C. Mancini, T. Nagayama, R. Tommasini, J. A. Delettrez, S. P. Regan, V. A. Smalyuk, R. Rodríguez and J. M. Gil, High Energy Density Phys. **6**, 70 (2010).
3. R. Florido, R. C. Mancini, T. Nagayama, R. Tommasini, J. A. Delettrez, S. P. Regan, B. Yaakobi, Physical Review E **83**, 066408 (2011).
4. R. Florido, R. C. Mancini, T. Nagayama, R. Tommasini, J. A. Delettrez, and S. P. Regan, Physics of Plasmas **21**, 102709 (2014).

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NLTE OPACITY CALCULATIONS IN ICF PLASMAS.
C+Si MIXTURES

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The opacity is an important issue in the knowledge of the radiative properties of Inertial Confinement Fusion (ICF) plasmas and astrophysical plasmas. In this work, we present the opacity of the mixture C+Si, where the silicon is a dopant embedded in the ablator of some ICF capsules. Hill and Rose [1] have recently calculated the opacity of silicon in LTE and non-LTE plasmas.

We have used the Cowan code to calculate the atomic structure of carbon and silicon in various ionic stages. The electron temperature and density were fixed to 300 eV and 6×10^{23} cm^{-3}, respectively. We have developed a collisional-radiative (CR) code in order to obtain the atomic levels populations and the ionic fractions. Line broadening mechanisms and line shift are taken into account in the opacity calculations. The ionization potential depression is included in both the CR model and the opacity calculations. The effect of a radiation field is examined.

We note that the CR and the LTE opacity results [2] show discrepancies mainly in the energy range [1900-2000] eV for the bound-bound contribution, and between 50 and 350 eV for the bound-free contribution.

References

[1] E. G. Hill and S. J. Rose, High Energy Density Physics **8**, 307 (2012).

[2] G. Mondet, F. Gilleron, J.-C. Pain, A. Calisti and D. Benredjem, High Energy Density Physics 9, 553 (2013)

HIGH DENSITY PLASMAS: WHEN THE AVERAGE ATOM IS NOT EQUIVALENT TO THE AVERAGE OF ATOMS

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The average atom model, being computationally inexpensive, is widely used in atomic and spectral modelling of plasmas. Despite its non-physical basis whereby it typically generates an "atom" with non-integer numbers of electrons in any given orbital, it is capable of remarkably realistic results over a wide range of conditions. Although the average atom model is rigorously correct within the framework of classical thermodynamics, it merely predicts a single (and, generally fictitious) atomic configuration of energy equal to the ensemble average energy - there is no *a priori* reason to expect that it should give the correct representation of the quantum mechanical properties of real entities within a plasma. In particular, at high densities, where the effects of continuum lowering determine whether the electronic wave functions are bound or unbound to the nucleus, the deviation of the average atom results from more rigorous calculations can be significant. Whilst there is some work in the literature which identifies the failures of the average model, with high energy density experiments now routinely investigating plasmas of solid density and greater, it is perhaps timely to illustrate some particularly egregious failures of the average atom model. In particular we show, by comparisons with detailed configuration accounting calculations from the DAVROS opacity code, that in cases where the average atom restricts sub-shells to a subset of a full shell (e.g. a cut-off at 3p, where the full shell would include 3d), configurations with sub-shells not bound in the average atom, can in fact form a considerable part of the partition function with significant effects upon related spectral quantities such as the Rosseland mean opacity.

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SELF-CONSISTENT DYNAMIC APPROCHES FOR THE CALCULATION OF PHOTOABSORPTION IN PLASMAS

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We present the calculation of photoabsorption within the framework of the dynamic self-consistent linear response of average-atoms in plasmas where all the electrons, bound and free, are treated on the same footing [1]. In the case of the quasi-classical Thomas-Fermi atom [2] at finite temperature, the method of the frequency-dependent linear response [3] relies on the knowledge of the outgoing wave behavior for the induced density and potential. The Variational Average-Atom in Quantum Plasma (VAAQP) [4] is a quantum extension of the Thomas-Fermi atom. The application of the self-consistent dynamic linear response [5] to the quantum model VAAQP enables to access to the interacting susceptibility and thus is expected to take into account the configuration interaction, including free electron configurations. Complex collective phenomena may also be included within this self-consistent treatment. However, we still do not retrieve in our calculations a collective outgoing plasma wave, such as in the quasi-classical model [6]. This absence of an outgoing wave is highlighted by the use of the Ehrenfest-type sum rule [7] and is presumed to be due to the much more complex asymptotic boundary conditions, that would have to be applied in the quantum model, and which stem from the non-local relation between the induced density and potential.

References

1. T. Blenski, R. Piron, C. Caizergues, B. Cichocki, HEDP **9**, 687 (2013).
2. R. P. Feynman, N. Metropolis, E. Teller, Phys. Rev. 75, 1561 (1949).
3. K. Ishikawa, B. U. Felderhof, T. Blenski, B. Cichocki, J. Plasma Phys. **60**, 787 (1998).
4. R. Piron, T. Blenski, PRE **83**, 026403 (2011).
5. T. Blenski, JQSRT **99** (1-3), 84 (2006).
6. C. Caizergues, T. Blenski, R. Piron, HEDP **12**, 12 (2014).
7. C. Caizergues, T. Blenski, R. Piron, HEDP **18**, 13 (2016).

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POSTERS: WARM DENSE MATTER

A Relativistic Green's Function Quantum Average Atom Model

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Quantum average atom models are widely used to calculate equation of state and other properties of warm and hot dense matter. A well known difficulty in these models is in finding free state resonances and very weakly bound states, requiring costly search algorithms to be implemented. To overcome this issue, we formulate a quantum average atom model using single particle Green's functions for both nonrelativistic and relativistic cases. The benefit of this formulation is that energy integrals can be taken into the complex plane, which broadens sharp features such as resonances and bound states. The result is that direct calculations can be carried out without the need for numerically expensive resonance tracking. This provides for a considerable speed-up with no change to the results of the model. We present the details of the formulation and examples of resonance broadening.

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POSTERS: ASTROPHYSICAL AND ATMOSPHERIC PLASMAS

DUST ACOUSTIC DRESSED SOLITON IN DUSTY PLASMA WITH SUPRATHERMAL IONS

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Dust is an ubiquitous component of space and astrophysical environments, occurring for example in planetary rings, comets and the Earth's ionosphere [1]. Dusty plasmas are known to support a wide variety of ultra low-frequency wave modes. The most well studied of such modes are the so called dust-acoustic wave (DAW) [2] and dust ion-acoustic wave (DIAW) [3]. The aim of this communication is to study a small-amplitude dust acoustic dressed solitons in a three component dusty plasma having electrons, suprathermal ions, and dust grains. We have then investigate the effect of ion suprathermality on small amplitude dust acoustic dressed wave and compared the result with the soliton's exact solution of the fourth order pseudo-potential and K-dV soliton.

References

1. D. A. Mendis, and M. Rosenberg, Annu. Rev. Astron. Astrophys. **32**, 419 (1994).
2. N.N. Rao, P.K. Shukla, and M.Y. Yu, Planet. Space Sci. **38**, 543 (1990).
3. P.K. Shukla, and V.P. Silin, Phys. Scr. **45**, 508 (1992).

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NONLINEAR DAMPING OF DUST ACOUSTIC WAVES IN A CHARGE VARYING ELECTRONEGATIVE DUSTY PLASMA

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The aim of the present communication is to investigate the charge variation induced nonlinear dust acoustic wave damping in a charge varying electronegative dusty plasma with nonthermal ions. It is shown that the collisionless damping due to dust charge fluctuation causes the nonlinear dust acoustic wave propagation to be described by a damped Korteweg-de Vries equation (dK–dV). The latter is significantly modified by the nonthermal negative ions effects. It may be useful to note that we consider nonthermal negative ions because of the role of their distribution into the formation and dynamics of nonlinear dust acoustic structures[1]. Moreover, the observation of nonthermal ion-distributions made by Phobos[2] and Nozomi[3] motivated us to consider non- Maxwellian ions.

References

1. A. V. Ivlev and G. Morfill, Phys. Rev. E 63, 026412 (2001).
2. R. Lundlin, A. Zakharov, R. Pellinen, H. Borg, B. Hultqvist, N. Pissarenko, E. M. Dubinin, S. W. Barabash, I. Liede, and H. Koskinen, Nature (London) 341, 609 (1989).
3. Y. Futaana, S. Machida, Y. Saito, A. Matsuoka, and H. Hayakawa, J. Geophys. Res. 108, 151, doi:10.1029/2002JA009366 (2003).

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IONIZATION AND HEATING OF A NEON GASCELL PHOTOIONIZED PLASMA EXPERIMENT AT THE Z FACILITY

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Detailed x-ray spectral observations performed with the Chandra and XMM-Newton orbiting telescopes provide critical information about photoionized plasmas in the universe. However, the complexity of the astrophysical environment makes the spectral analysis challenging, and thus laboratory experiments are important for data interpretation and benchmarking of modeling codes [1]. The Z facility at Sandia National Laboratories is a powerful source of broadband x-rays to produce and study in the laboratory photoionized plasmas relevant to astrophysics under well characterized conditions. We discuss an experimental and theory/modeling effort in which the intense x-ray flux emitted at the collapse of a z-pinch implosion driven by the Z pulsed-power machine is employed to produce a neon photoionized plasma. The broadband x-ray radiation flux from the z-pinch creates the plasma and provides a source of backlighting photons to probe it through K-shell line absorption spectroscopy. The plasma is contained in a cm-scale gas cell that can be located at several distances from the z-pinch and filled with different neon gas pressures. The flexibility of the set up permits a systematic study of the photoionized plasma for a range of ionization parameter values between 1 and 100 erg cm / s. The plasma is diagnosed via transmission spectroscopy using a spectrometer equipped with two elliptically-bent KAP crystals and a set of slits to record up to six spatially-resolved spectra per crystal in the same shot [2]. The transmission data shows a rich line absorption spectrum that spans several ionization stages of neon including Be-, Li-, He- and H-like ions. Modeling calculations are used to interpret the transmission spectra recorded in the experiments with the goal of extracting the charge-state distribution, electron temperature, spectral distribution of the x-ray drive, and the ionization parameter of the plasma. In addition, we discuss the heating of the plasma and the comparison between the electron temperature extracted from data analysis and modeling results from radiation-hydrodynamics and Boltzmann kinetic simulation codes.

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References

1. R. C. Mancini, J. E. Bailey, J. F. Hawley, T. Kallman, M. Witthoeft, S. J. Rose and H. Takabe, Phys. Plasmas **16**, 041001 (2009).
2. I. M. Hall, T. Durmaz, R. C. Mancini, J. E. Bailey, G. A. Rochau, I. E. Golovkin and J. J. MacFarlane, Phys. Plasmas **21**, 031203 (2014).

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POSTERS: MAGNETIZED PLASMAS

DEVELOPMENT OF A TEMPERATURE DIAGNOSTIC IN FLUORINE-LIKE ALUMINUM EMISSION IN THE EUV

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We studied aluminum emission in the 115-320 Å extreme ultraviolet spectral region on the Lithium Tokamak Experiment at the Princeton Plasma Physics Laboratory. Spectra were taken with the Long Wavelength Extreme Ultraviolet Spectrometer, LoWEUS, which has a resolution of ~0.3 Å [1]. We identified emission from neon-like Al IV and fluorine-like Al V. Our data include emission from Li II and Li III, and O IV-VI, which we used for wavelength calibration. We used oxygen intensities from the CHIANTI database [2, 3] to calculate an intensity response function for the region we studied. The aluminum emission was compared to calculations using the Flexible Atomic Code [4]. We calculated theoretical intensities of fluorine-like Al V at electron temperatures T_e from 1 eV to 850 eV, and found that some line pairs are temperature sensitive. In particular, we show that the ratio of the intensity of the 3→2 feature at 133 Å to a pair of 2→2 lines at 278 Å and 281Å can be used to derive temperature estimates for the emitting region of the plasma. Our measurements indicate a temperature T_e of ~16 ± 2 eV from the λ 133/278 line pair and ~17.5 ±2 eV from the λ 133/281 line pair.

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References

1. J. K. Lepson, P. Beiersdorfer, J. Clementson, M. F. Gu, M. Bitter, L. Roquemore, R. Kaita, P. G. Cox, and A. S. Safronova, J. Phys. B., **43**, 142010 (2010).

2. K. P. Dere, E. Landi, H. E. Mason, B. C. Monsignori Fossi, and P. R. Young, Astron. Astrophys., **125**, 149 (1997).

3. E. Landi, P. R. Young, K. P. Dere, G. Del Zanna, and H. E. Mason, Astrophys. J., **763**, 86 (2013).

4. M. F. Gu, Can. J. Phys., **86**, 675 (2008).

Turbulence and Transport Barrier Relation with Poloidal Magnetic Field in Damavand Tokamak

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Abstract

Experimental measurement of poloidal magnetic field B_p, in elliptical cross section of Damavand Tokamak has been carried out. This cross section is divided in to four regions labeled (1) to (4). Our results showed that the values of B_p in region (3) are greater than other regions. Overlapping of magnetic Islands in the region (3) is pronounced and the width of magnetic islands in this region is smaller than other regions. The thickness of transport barrier is not uniform around all periphery of the barrier transport layer. The turbulence effects can modify the transport barrier from the lower left side of mid plan of cross section to upper side of mid plan section.

Poloidal cross section of Damavand tokamak is in the quasi elliptic with elongation of k=1.2, B_t=1T, R_0= 36cm, maximum plasma current I_p= 35KA and discharge time is about 21ms. Experimental measurement of poloidal magnetic field has been measured with 18 magnetic probes which are placed on the interior edge of the Damavand tokamak vacuum vessel.

Transport barrier in toroidal plasma is considered as edge region between hot and cold phase plasma. These two phases have different collision transport properties so that boundry region between them corresponds to lower values of specific resistivity and transport coefficient of plasma. Behavior of shear magnetic in this region of transport and some other specific of transport barrier resulted from plasma resistivity in this region. Obtained long time of magnetic confinement is controlling the turbulence near the vessel wall. Characteristic of turbulence level and their effects to transport of energy and particle has important role.[1,2,3]

Existence of Transport barrier in Damavand tokamak showed that thickness of transport layer is not uniform in all poloidal cross section and values of B_p is greater in region (3) and poloidal B_p is compressed in this region while B_p values in the region (1) are lower than region (3). The width of magnetic islands and their overlapping are smaller than other regions.

Reference:

[1] – L.Zeng et al, Experimental observation of a magnetic turbulence threshold for runaway electron in the TEXTOR Tokamak, Physical Review Letters, 235003-1, 2013.

[2]- T. Fulop, G. Pokol, P. Helander, M. Lisak, destabilization of magneto sonic whistler waves by relativistic runaway beam, Phys, Plasma, 13, 062506, 2006.

[3] – M. Forster et al, runaway transport in turbulent and resonantly perturbed magnetic topology of Textor, Nucl, fusion,52, 2012.

STARK BROADENING BY RELATIVISTIC ELECTRONS IN MAGNETIC FUSION PLASMAS

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Highly energetic runaway electrons (REs) pose a major threat for future large scale tokamak fusion reactors and are a matter of great concern for their long term operability. These relativistic REs can cause a major damage to the in-vessel components and the first wall causing a major shutdown. The behavior of runaway electrons was theoretically and experimentally studied in various tokamaks in the past few decades and is fairly well understood. However, there are still some gaps in presently available theoretical models and experimental observations. In this work, we examine the possibility for a diagnostic of REs based on the passive spectroscopy of atomic lines in the core and edge region of tokamaks. A still pending issue concerns the role of the microfield on the line broadening and the (Liénard-Wiechert) correction to the Coulomb formula due to the relativistic motion of REs. We examine this point and perform new calculations of hydrogen Lyman and Balmer lines. The broadening of impurity lines will also be examined.

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POSTERS: X-RAY SOURCES

INVESTIGATION OF BRIGHT 13 KEV KR K-SHELL X-RAY YIELDS AT THE NATIONAL IGNITION FACILITY

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High conversion efficiency (CE) K-shell sources are being developed for High Energy Density (HED) experiments and for the testing of materials exposed to high x-ray fluences. Recently, sources with high CE in the Kr K-shell have been developed at the National Ignition Facility. The previous work in 2012 [1] has reported $\sim$ 3% conversion of the laser energy into Kr K-shell ($\sim$ 13 keV) radiation, consistent with theoretical predictions. These targets were 4.1 mm in diameter 4.4 mm tall hollow epoxy tubes having a 40 μm thick wall holding either 1.2 or 1.5 atm of Kr gas. For these shots, the laser delivered $\sim$ 700 kJ of 351 nm (3ω) light in a 5 ns flattop pulse at a peak power of $\sim$ 140 TW.

The CE of Kr is dependent upon the peak electron temperature in the radiating plasma. In the NIF experiments, the available energy was not sufficient to heat the targets to a high enough temperature (T_e(NIF) = 6-7 keV) for the Kr CE to be optimal. The CE is a steep function of the peak electron temperature in this region. A spatially averaged electron temperature can be estimated from measured He_α and Ly_α line ratios. Some disagreement has been observed in the simulated and measured line ratios for some of these K-shell sources. This implies that some uncertainties in the model may exist. To help understand this issue, additional Kr gas pipes have been shot in 2014 with $\sim$ 750 kJ at $\sim$ 210 and $\sim$ 120 TW power levels with 3.7 and 6.7 ns pulses, respectively. The power and pulse length scaling of the measured CE and K-shell line ratios and their comparison to simulations will be discussed.

This work was performed under the auspices of the US Department of Energy by University of California Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48. This work was also supported by the Defense Threat Reduction Agency under the interagency agreements No. 10027-1420 and No. 10027-6167.

References

1. K. B. Fournier et al., Phys Rev E. **88**, 033104 (2013).

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LECTURES

Spectral Lines in Plasmas, Yu. Ralchenko

Most of information on properties and evolution of plasmas, from fusion devices and solar corona to EUV light sources for lithography to dense laser-produced plasmas, comes from analysis of their spectra. Whereas the continuum (free-free and free-bound) emission may at times be useful for diagnostics, it is primarily the spectral lines originating from transitions between bound states that deliver the bulk of data on diverse parameters such as plasma density and temperature, electromagnetic fields, and particle energy distributions, to name a few. This lecture will address the current understanding of physical processes responsible for line emission in plasmas as well as outline the typical strategies for spectroscopic plasma diagnostics in various environments.

Population Kinetics Modeling For Plasma Spectroscopic Analysis ȟ (8ζ + 8#ÈÕÎÇ

- General description of population kinetics modelling
- Demonstration of FLYCHK simulations for various plasma studies.

The goal is to provide basic understanding of atomic processes in plasmas and population kinetics modelling used for plasma spectroscopic analysis. The lecture will provide details on how to build a population kinetics model and demonstrate how to use a generalized population kinetics code FLYCHK available at

http://nlte.nist.gov/FLY/

for laser-produced plasmas, photo-ionized plasmas, radiative loss rates, two temperature plasmas and so on.

Spectral lineshape modeling state of art, A. Calisti

Spectroscopic measurement of the line transitions is one of the richest sources of diagnostic information about plasma properties. The diagnostic is then based on the comparison of observed and modeled spectra for partially puzzling out hidden information. Evidently, to be reliable, this requires accurate theoretical models of atomic and radiation physics.

This lecture will cover:

- The importance and role of spectral line profiles in the diagnosis of plasma properties, the formation of opacity and the radiation transport.
- The theoretical formulation for spectral line profiles illustrating first, the concept of separation of ion and electron broadening mechanisms and the formation of spectral lines, and second, the additional mechanisms such as Doppler Broadening, magnetic field effects and instrumental broadening affecting the line shape.
- Illustration by examples of spectroscopic diagnostics in laser-plasma, inertial fusion and Tokamak experiments.

An introduction to the interaction of X-ray free electron laser radiation with matter, F. Rosmej

The lecture provides an introduction to the physics of the interaction of X-ray Free Electron Laser (XFEL) radiation with matter. Unlike optical lasers, where energy absorption is essentially realized by inverse Bremsstrahlung and parametric instabilities, the primary absorption mechanism of XFEL is photoionization of atomic shells. Due to the large photon energy (up to 20 keV), XFEL radiation photoionizes mainly inner atomic shells thereby creating very exotic states [1,2]: hollow atoms/ions, hollow crystals. The atomic physics processes related to these exotic states are essential to understand XFEL interaction with matter and the temporal evolution from a solid to Warm Dense Matter (WDM).

Astrophysical X-ray spectra, J. Kaastra

The various way X-ray spectra of astrophysical sources are being measured and formed under different astrophysical conditions, ranging from collisional equilibrium, photoionisation equilibrium and non-equilibrium ionisation conditions. I will give an overview of the relevant processes that play a role under these conditions, and their link to the basic atomic processes. I will also show some example spectra for the various cases.

Can we nurse the fire? The physics of magnetic fusion, D. Reiter

With the first net power producing fusion plant ITER now being under construction, in a worldwide collaborative effort, controlled nuclear fusion research ushers in a new era. For the first time a controlled thermonuclear burning fire is expected to be ignited on earth. In this tokamak ITER in Cadarache (France) in about a decade from now, plasmas with a fusion power of 500 MW at an external heating power of 50 MW can be magnetically confined.

According to current knowledge, which is based on extrapolation from a huge experimental and theoretical basis build up over half a century, the ignition of a plasma flame in a tokamak magnetic confinement devise of the scale of ITER seems secured. But new challenges arise on the next step from ignition towards maintaining the plasma flame, continuous duty, in equilibrium also with the walls of the furnace chamber, under nuclear conditions. These issues are not yet solved.

The major magnetic confinements concepts in controlled fusion research: tokamaks and stellarators, will be introduced, their pros and cons, and their status of development relative to the requirements of a first power plant targeted for the middle of the present century.

The role of atomic processes in such thermonuclear burning hydrogenic plasmas will briefly be introduced. This will be covering the range from hot plasma physics (all chemical bonds broken) for core plasma diagnostic (plasma spectroscopy) up to the chemically rich plasma boundary near the walls, the latter with processes in energy ranges partially overlapping with those in (technical) low temperature plasma or astrophysical plasma (stellar and planetary atmospheres) applications.

Author Index

Aanesland Ane, 31
Abdallah Joseph, 19, 102
Ait Mammar Sofiane, 77
Ali Safdar, 5
Alinejad Naser, 105
Allan Peter, 9
Allen S. L., 14
Amour Rabia, 100
Angelo Paulo, 62
Annaloro Julien, 44
Aranchuk Leonid, 60
Aslanyan Valentin, 66

Badnell Nigel, 55
Bailey Jim, 10, 102
Ballance Connor, 4, 6, 81
Banas Dariusz, 16
Bang Jinyoung, 84
Banici R. A., 25
Barnsley Robin, 106
Barrios Maria, 108
Bartnik Andrej, 32, 90
Bastiani-Ceccotti Serena, 61
Bautista Manuel, 6
Bauville Grad, 86
Baynard Elsa, 25
Bedrane Zeyneb, 71
Beiersdorfer Peter, 9, 72, 104
Beilmann Christian, 76
Ben Nessib N, 68
Benallal Rafik, 85
Benredjem Djamel, 73, 94
Benzekka Moufida, 101
Besmehn Astrid, 41
Blaess Christophe, 77
Blancard Christophe, 10
Blenski Thomas, 61, 96
Bommier Véronique, 21
Boudghene Stambouli Arslane, 85
Boyle Dennis, 104
Brage Tomas, 22
Brandt Christian, 46
Bredin Jérôme, 29
Brown C. R. D., 9
Brown Gregory , 72
Bufferand Hugo, 13
Bultel Arnaud, 44, 73
Burks E., 38

Caizergues Clément, 96
Calisti Annette, 8, 64, 112
Carbajal-Gomez Leopoldo, 13
Carniato Stéphane, 45
Chabert Pascal, 31
Chakrabarti Kalyan, 73
Champion Norbert, 77
Charnvanichborikarn S., 38
Chavel Pierre, 40
Chen Hui, 9
Chen Mau, 3
Chung Hyun-Kyung, 3, 35, 111
Ciraolo Guido, 13
Ciricosta Orlando, 3
Cojocaru G. V. , 25
Colboc Florian, 73
Colgan James, 10, 19
Colvin Jeff, 38, 108
Comet Maxime, 79, 92
Condamine Florian 61, 62
Cossé Philippe, 10
Creel James, 30
Crespo López-Urrutia J. R., 76, 82

Danisman Yusuf, 60
Dedrick James, 29
Delettrez J. A., 93
Delmas Olivier, 25
Demailly Julien, 25
Denis-Petit David, 92
Depresseux A, 39
Deprince Jérôme, 74
Deschaud Basil, 36
Dharma-Wardana M. W. Chandre, 65
Dickheuer Sven O., 46
Dimitrijević M. S., 68
Dobrodey Stepan, 82
Donnelly Tony, 30
Dozières Maylis, 61, 62
Dreiling Joan, 80
Druguet Marie-Claude, 44
Dunne Padraig, 24

Emig Jim, 9
Epée Epée Michel Douglas, 73
Es-Sebbar Et-Touhami, 86

Faussurier Gérald, 10
Felter T., 38
Ferri Sandrine 8, 64
Fiedorowicz Henryk, 32, 90
Fivet Vanessa, 6
Flacco A, 39
Fletcher L. B., 35
Fleury Michel, 86
Florido Ricardo, 93
Fok T, 32
Fontes Chris, 10, 18, 19
Fournier Kevin, 38, 108
Fritzsche Stephan, 74
Förster Eckhart, 42

Galtier Eric , 35
Gamboa E. J., 35
Gans Timo, 29
Gautier J, 39
Gazeli Kristaq, 86
Genesio P, 8
Gill Nathanael, 98
Gillaspy John, 80
Gilles Dominique, 79
Gilleron Franck, 10, 49, 61, 79, 92
Glenzer Siegfried, 35
Gobet Franck, 92
Godbert-Mouret Laurence, 15
Goddet J. P., 39
Golovkin I, 10
Gosselin Gilbert, 92
Green Jonathan, 87
Gribakin Gleb, 54
Grondein Pascaline, 31
Gudmundsson Jon, 28
Guilbaud Olivier, 25, 40
Gumberidze Alexander, 16
Guzik J. A., 19

Habchi Mohammed, 85
Hakel Peter, 19
Hannachi Fazia, 92
Hannachi Ibtissem, 105
Hansen Stephanie, 10
Hara Hirohisa, 5
Harbour Louis, 65
Hardtdegen Hilde, 41
Harris James, 9
Hassouni Khaled, 73
Heeter R, 102
Hibbert Alan, 81
Higashiguchi Takeshi, 24

Hill Matthew, 9
Hoarty David, 9
Hobbs Lauren, 9
Hoekstra Ronnie, 26, 82
Hoffmann Andreas, 42
Höfer Sebastian, 42
Hutton Roger , 22

Iaquaniello G, 39
Iglesias Carlos, 10, 52
Ilie Simona, 73
Indelicato Paul, 56
Iorga Cristian, 69

Jacquemot Sylvie, 39
Jagodzinski Pawel, 16
James Steven, 9
Jarocki R, 32
Jarrah Walid, 94
Jon Grumer, 22
Jung Young-Dae, 75
Juschkin Larissa, 41

Kaastra Jelle, 20, 114
Kaita Robert, 104
Kallman Timothy, 6, 74
Kang Taekyun, 84
Kartashov Daniil, 42
Kato Daiji, 5
Kazamias Sophie, 25
Kemp Gregory, 108
Khaghani Dimitri, 42
Kilbane Deirdre, 24
Kilcrease David, 10, 19
Kim H. T., 39
Klapisch Marcel, 51
Klisnick Annie, 25, 40
Klug Dennis D. , 65
Koubiti Mohammed, 15
Kozlova M, 39
Kucheyev S., 38
Kurilovich Dmitry, 26

Lafleur Trevor, 31
Lambert G, 39
Landgraf Björn, 42
Larour Jean, 60
Larroche Olivier, 40
Laska A, 72
Le Marec Andréa, 25, 40
Lee Hyochang, 84
Lee H. J., 35
Lee Richard W, 3

Lee Upcraft, 95
Lefrou T, 39
Lepson Jaan, 104
Letourneur Bruno, 88
Lewis Laurent J, 65
Li Bowen, 24
Li Wenxian, 22
Liang Guiyun, 76
Liedahl D, 102
Lifschitz A, 39
Little Duncan, 73
Liu Kai, 38
Lockard T. E., 102
Loisel Guillaume, 10, 102
Lokasani R, 24
Long Elaine, 24
Lucas Bruno, 25
Lunney James G., 30

MacFarlane J. J., 10
Macé Jean-Sébastien, 88
Magee Edward, 9
Magee N. H., 19
Majeski Richard, 104
Malka Victor, 39
Mancini Roberto, 10, 58, 93, 102
Marandet Yannick, 13, 15, 106
Marchuk Oleksandr, 46
May Mark, 38, 108
Mayes D. C., 102
Maynard Gilles, 39, 88
McLean A. G., 14
Meftah Ali, 77
Mendoza Claudio, 6
Méot Vincent, 92
Mesli Sidi Mohamed, 85
Mezei Zsolt, 73
Minea Tiberiu, 88
Moreau N, 68
Morel Pascal, 92
Morel Vincent, 44, 73
Morton John, 9
Moslehi-Fard Mahmoud, 105
Mossé Caroline, 8
Motapon Ousmanou, 73
Murakami IIzumi, 5
Mussack K. A., 19

Nace Nicolas, 13
Nagayama T, 10, 93
Nahar Sultana, 10
Nakamura Nobuyuki, 5
Nejdl J, 39
Neumayer Paul, 42
Neveu Olivier, 86
Niemi Kari, 29
Nikravech Mehrdad, 89
Niyonzima Sébastien, 73
Nolte Jeffrey, 6
Noman Hala, 78

O'Connell Deborah, 29
O'Reilly F, 24
O'Sullivan Gerry, 24
O'Mullane Martin, 55
Oliva E, 39
Orban C., 10

Pain Jean-Christophe, 10, 49, 61, 79, 92
Pais Vasile, 69
Pajek Marek, 16
Palmeri Patrick, 74
Pandya Santosh, 106
Pasquiers Stephane, 86
Patel Mehul, 108
Pérès Bastien, 73
Perez F., 38
Peyrusse Olivier, 8, 36
Piron Robin,96
Pittman Moana, 25
Poirier Michel, 61
Pop Nicolina, 73
Pospieszczyk Albrecht, 46
Pradhan A. K., 10
Preval Simon, 55
Puech Vincent, 86
Puglisi Alessandra, 45

Quinet P, 6, 74

Rahmani Abdelkader, 89
Ralchenko Yuri, 2, 80, 110
Ramsbottom Cathy, 4, 81
Redmer R, 35
Regan S. P., 93
Reichle Roger, 106
Reinholz H., 35
Reiter Detlev, 12, 115
Renner Oldrich, 62
Reverdin C. , 61
Rieß Sally, 41
Rochau Greg, 10, 102
Ronning Carsten, 42
Ros David, 25
Rosato Joel, 15, 106

Rosmej Frank, 36, 61, 62, 113
Rosmej Olga, 42
Rousse Antoine, 39
Rousseau P, 39
Rudolf Denis, 41
Röder Robert, 42
Röpke G. , 35

Saber Ismail, 90
Sadighzadeh Asghar, 105
Sahal-Bréchot Sylvie, 68
Sakaue Hiroyuki A, 5
Samsonova Zhanna, 42
Santos Sousa Joao, 86
Scheers Joris, 26
Schmitz Christoph, 41
Schmitz Oliver, 87
Schneider Claus M., 41
Schneider Ioan, 73
Schröter Sandra, 29
Schuck Martin, 41
Scott Howard, 59, 108
Sebban Stéphane, 39
Serre Eric, 13
Severn Greg, 87
Sheil John, 24
Shepherd Ronnie, 9
Sherrill M. E., 10, 19
Shimizu Erina, 5
Silvert Virginie, 61
Silwal Roshani, 80
Sisourat Nicolas, 45
Skrzeczanowski W, 32
Šmíd Michal, 62
Sokell Emma, 24
Soukhanovskii Vlad, 14
Soullié G, 61
Sperling Philipp, 35
Spielmann Christian, 42
Stamm Roland, 15, 106
Stancalie Viorica, 69
Starrett Charles, 98
Stöhlker Thomas, 16
Suzuki Chihiro, 24

Ta Phuoc K, 39
Takacs Endre, 80
Tafzi A, 39
Talin Bernard, 8, 64
Tallents Greg, 66
Tamain Patrick, 13
Tarisien Medhi, 92
Tauheed Ahmad, 78
Tautz F. Stefan, 41
Tchang-Brillet Lydia, 77
Tennyson Jonathan, 73
Thais Frédéric, 61, 62
Thaury C, 39
Tissandier F, 39
Tommasini R., 93
Torretti Francesco, 26, 82
Trefflich Lukas, 42
Tribeche Mouloud, 100,101
Tsuda T, 5
Turkington Michael, 81
Tyndall Niall, 4

Ubachs Wim, 26, 82
Ungureanu R. G., 25
Upcraft Lee, 95
Ursescu D, 25
Uschmann Ingo, 42

Valentinuzzi Matteo, 13
Versolato Oscar, 26, 82
Versteegen Maud, 92
Villette B, 61
Vinko Sam, 3
Vodungbo B, 39
Von Marley Edward, 9

Wachulak P, 32
Wagenaars Erik, 29
Walczak P, 19
Wark Justin, 3, 34
Watanabe Tetsuya, 5
Wegrzyński L, 32
Wei H. G., 76
West Andrew, 29
Widmann Klaus, 108
Wiemann Carsten, 41
Wilson Brian, 10
Wilson Daniel, 41
Windberger Alexander, 82
Witte B. B. L., 35
Wu Tao, 24
Wyart Jean-François, 48, 77

Yilmaz M. Fatih, 60

Zastrau U, 35
Zeitoun Philippe, 39
Zhao G, 76
Zou Yaming, 22
Zürch Michael, 42