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Abstracts of Posters

Accurate Mn I line profiles in the H-band

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Hyperfine splitting of Mn I line profiles can be observed in the visible and infrared spectrum of the sun. [1] noted that the strong (log(gf) $>$ -0.5) Mn I lines at 17325, 17339 and 17349 Å in the H-band have broad hyperfine splitting and appear to be blended with unknown features in the solar spectrum. There are no hyperfine structure constants in the literature for the upper levels (w^6F_J) of these transitions and the fine structure energies are poorly known. The NIST atomic level database [2] provide values from a work from 1964 where the energies were extracted using a method which gave very large uncertainties.

[3] identified the 17325 Å feature as a blend of the $e^6D_{9/2} - w^6F_{11/2,9/2,7/2}$ transitions, the 17339 Å feature as a blend of $e^6D_{7/2} - w^6F_{9/2,7/2,5/2}$ and 17349 Å as $e^6D_{5/2} - w^6F_{7/2,5/2,3/2}$. However, [4] found that it was not possible to fit the transitions from w^6F_J using hyperfine constants and indicated that the hyperfine splitting of the blended 17325, 17339 and 17349 Å lines may require a more detailed theoretical analysis to fully understand these line profiles.

To investigate the hyperfine structure of these lines a spectrum was obtained using the infrared Fourier Transform Spectrometor of the Edlén laboratory in Lund. Calculations was then performed to reproduce the experimental spectrum synthetical allowing us to extract the information such as the energy of the hyperfine levels and the gf-values of all the hyperfine lines. Starting from large scale MCDHF calculations, good J-dependent wave functions were obtained for the upper and lower states. These was then used in the newly developed programs HFSMIX and HFSTRANS [5] to investigate the hyperfine structure. Before including the hyperfine interaction the lower fine structure energies were adjusted to experimental values. However, no good experimental values are known for the upper and we therefore deduced these through an iterative procedure. Using the error defined by the least square fit between the synthetic and experimental spectra, we started by fitting a Landé constant and then further adjusted these energies by varying the individual fine structure levels. Using this method good agreement was found between the synthetic and experimental spectra.

It was found that the off-diagonal hyperfine interaction for w^6F_J in many cases were so strong that J was no longer a useful quantum number. As a consequence were the hyperfine induced intensity redistribution among the hyperfine lines extremely large and we found that the 17325, 17339 and 17349 Å features consists of many more lines than predicted by [3].

Using the determined wave lengths and gf-values for the individual hyperfine lines we could also model a part of the solar spectra that earlier has not been fully understood.

[1] J. Meléndez, MNRAS, **307**, 197 (1999)

[2] Y. Ralchenko *et al.*, NIST Atomic Spectra Database (version 3.1.5) (2008)

[3] A.G. Taklif, Phys. Scr., **42**, 69 (1990)

[4] R.J. Blackwell-Whitehead, Ph.D. thesis, Imperial College, London (2003).

[5] Grumer and Andersson, unpublished.

The FERRUM Project: Experimentally determined lifetimes of the metastable $c^4D_{5/2}$ and $c^4D_{7/2}$ levels in Cr II

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The FERRUM Project [1] is an ongoing project to get new and accurate atomic data of the iron group elements. In low density plasma regions of space e.g. the *strontium filament* found in the ejecta of η Carinae, radiative decay of long lived metastable states becomes important and can be observed. The measured metastable levels lifetimes can be used together with branching fractions to obtain absolute transition rates [2], which in turn can be used to extract information about the abundances of elements [3].

We report lifetimes of the metastable energy levels c $^4D_{7/2}$ and c $^4D_{5/2}$ in Cr II. They have been measured by time resolved laser spectroscopy. The study has been performed at the CRYRING ion storage ring in Stockholm, Sweden. Earlier calculations by Quinet [4] reported lifetimes of 1.40 s and 1.33 s respectively. Another calculation by Nussbaumer et al. [5] gave the lifetimes 1.52 s and 1.61 s respectively. The experimental lifetimes appear to be significantly shorter than the available calculated values and a new theoretical investigation is therefore under way.

[1] Johansson, S. et al. Phys. Scr., **T119**, 61, 2002
[2] Gurell, J. et al. A&A. **508**, 525, 2009
[3] Bautista, M.A. et al. Mon. Not. R. Astron. Soc. **393**, 1503, 2009
[4] Quinet, P. Phys. Scr. **55**, 41, 1997
[5] Nussbaumer, H. et al., Astrophys. J. **162,** 589, 1970

FeII and heavy-element lines in the HST-STIS spectrum of the uranium-rich metal-poor star CS31082-001

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Abstract

The near-ultraviolet region presents a large number of lines of the heavy elements, and in the case of some elements such as Pt, Au, detectable lines are not available elsewhere. A wealth of FeII lines is also present in this wavelength region.

In the process of deriving abundances for the uranium-rich metal-poor star CS 31082-001 we are able as well to check line lists available in the ultraviolet.

The extreme "r-process star" CS 31082-001 ([Fe/H] ~ -2.9) was observed in the near-UV in order to determine its abundances of the heaviest stable elements, from absorption lines that are only reachable in the near UV, using STIS on board HST. We will report abundance derivation of heavy r-elements from a series of available lines, and point out the difficulties.

Transition Probabilities in Heavy Elements and Ions (37≤Z≤86) and the Specific Case of Tungsten.

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The heavy elements and ions of the periodic table (5^{th} and 6^{th} rows, lanthanides) have been rather little investigated until recently, due to the numerous difficulties met both on the theoretical and on the experimental sides. In relation with the recent needs in astrophysics and in plasma physics, the situation has evolved recently and substantial progress has been reported. This progress has been made easier by the developments of theoretical methods and also by the extensive use of laser spectroscopy.

Having in mind the astrophysical context and the thermonuclear controlled fusion needs, we have started a systematic investigation of the radiative parameters of these ions (neutral, singly and doubly ionized elements) about ten years ago. As a consequence, a large number of new results have been obtained. They are stored in two databases, DREAM [1] and DESIRE [2], which are regularly updated on web sites of Mons University in Belgium.

About 650 lifetimes have been measured by TR-LIF spectroscopy at the Lund Laser Centre, in Sweden, for the elements Rb to Xe, Cs to Rn and for the lanthanides. The combination of these lifetimes with theoretical (and, when possible, experimental) branching fractions has led to transition probabilities for about 65 000 (DREAM) and 13 000 transitions (DESIRE), respectively.

Radiative data for the tungsten ions are of utmost importance in fusion devices (Tokamaks). During the meeting, we will discuss the specific cases of W I, W II and W III ions and a critical survey of the available transition probabilities for these three ions will be presented. Original results, obtained for the forbidden transitions, will also be discussed [3].

[1] É. Biémont, P. Quinet, Phys. Scr. T**105**, 38 (2003); É. Biémont, Phys. Scr. T**119**, 55 (2005); http://www.umh.ac.be/~astro /dream.shtml.

[2] V.Fivet, P. Quinet, P. Palmeri, É. Biémont, H.L. Xu, 2007 J. Electron. Spectrosc. Relat. Phenom. **156-158**, 250 (2007); http://www.umh.ac.be/~astro /desire.shtml.

[3] P. Quinet, V. Vinogradoff, P. Palmeri, É. Biémont, J. Phys. B (in press).

Hyperfine quenching in Be-, Mg- and Zn-like ions

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The hyperfine quenching of the $nsnp\,^3P_2$ hyperfine level in the Be-, Mg- and Zn-like iso-electronic sequence were investigated in [1], [2] and [3] respectively. To the best of our knowledge have the quenching of these states earlier only been investigated for neutral Magnesium by [4] and [5] and neutral Zink by [4]. We present an overview of the results and give a general discussion about the results along the homologous sequence as well as pointing towards some potential problems this quenching could introduce into density diagnostics of un-dense astrophysical plasmas.

Much more work has been performed concerning the hyperfine quenching of $nsnp\,^3P_0$. We compare our results for these types of hyperfine quenching to available experiments and the differences are discussed. We also compare our results to other theoretical works and the differences are explained.

References

[1] M. Andersson *et al.*, Phys. Rev. A **79** 032501 (2009).

[2] M. Andersson *et al.*, J. Phys. B **43** 095001 (2010).

[3] M. Andersson *et al.*, Phys. Rev. A **78** 062505 (2008).

[4] R.H. Garstang, J. Opt. Soc. Am **148**, 845 (1962)

[5] S.G. Porsev and A. Derevianko, Phys. Rev. A **69** 042506 (2004)

Configuration interaction calculation of allowed and forbidden transitions in Fe II

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Earlier configuration interaction calculations of Fe II E1 transitions by our group (for example, [1], [2]) have been extended in the number of symmetries incorporated as well as the number of configurations used, and also to forbidden (E2 and M1) lines. In the poster we will present a small selection of our results, focusing on transitions which relate to astrophysical observations and laboratory measurements. The work has been completed using the general atomic structure package CIV3 [3,4]. The A-values of many of the transitions are substantially influenced by CI mixing in the wave functions of one or both of the states of the transition. We will discuss how this mixing can be determined as accurately as possible.

Some of our work has already been published [5]. A sensitive test of the relationship between theory and observation in the study of transitions observed in active galactic nuclei is the [Fe II] $\lambda12567/\lambda16435$ line ratio. These two transitions have the same upper level ($a\ ^4D_{7/2}$) so the flux density ratio is related to the ratio of the A-values. The ratio has been studied by a number of different theory groups as well as several observational teams. Our results confirm the earlier values of Nussbaumer and Storey [6] but are somewhat further from those of Quinet *et al* [7]. Of the rather wide range of observational results, we agree closely with unpublished results of Everett and Bautista, but find that those of Smith and Hartigan [8] are somewhat too high, while the majority of the observations of Rodriguez-Ardila *et al* [9] give much smaller values for this ratio.

Amongst comparisons with experimental work, we agree closely with the lifetime of $3d^6(^3H)4s\ ^2H_{11/2}$ measured by Hartman *et al* [10]. Other comparisons will be presented in the poster.

[1] G. Corrégé and A. Hibbert, ApJ, **627**, L157 (2005).
[2] G. Corrégé and A. Hibbert, ApJ, **636**, 1166 (2006).
[3] A. Hibbert, Comp. Phys. Commun., **9** 141 (1975).
[4] R. Glass and A. Hibbert, Comp. Phys. Commun., **16** 19 (1978).
[5] N.C. Deb and A. Hibbert, ApJ, **711**, L104 (2010).
[6] H. Nussbaumer and P.J. Storey, A&A, (bf 193, 327 (1988).
[7] P. Quinet *et al*, A&AS, **120**, 361 (1996).
[8] N. Smith and P. Hartigan, ApJ, **638**, 1045 (2006).
[9] A. Rodriguez-Ardila *et al*, A&A, **425**, 457 (2004).
[10] H. Hartman *et al*, A&A, **397**, 1143 (2003).

Transition Probabilities of Neutral Rare Earths – Er I and Gd I

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The current work is part of an on-going study of transition probabilities of rare earth neutrals. Transition probabilities are determined using the well-established technique of combining radiative lifetimes measured using time-resolved laser-induced fluorescence on a slow atomic beam with branching fractions measured from high resolution Fourier-transform spectra. These measurements are motivated by needs in both the lighting research and astrophysics communities. Rare earth spectra are very complex owing to open 4f, 5d, 6s and 6p shells, which result in a large number of low-lying overlapping configurations of both parities. This gives rise to rich spectra comprised of 100's to 1000's of transitions throughout the visible and near UV. These properties make rare earths valuable additives (in the form of rare earth salts) to Metal Halide - High Intensity Discharge (MH-HID) lamps, giving them a pleasing white light with good color-rendering. MH-HID lamps are an important technology going forward because of their high efficacy (a factor of 5 or 6 above incandescent). Transition probabilities of both the first and second spectra of the rare earths are needed by lighting scientists for diagnostic and modeling of these lamps. Rare earth transition probabilities are also needed within the astrophysics community to determine rare earth abundances in stellar photospheres. In particular, transition probabilities of neutral rare earths will be helpful in improving abundances in cool stars in which a significant fraction of rare earths are neutral in the photosphere.

This poster presents recently finished work in neutral erbium, for which radiative lifetimes have been measured for 123 levels[1]. Branching fractions have been measured for a majority of these levels, and we report transition probabilities for several hundred transitions of Er I. Measurements are also underway for radiative lifetimes and branching fractions of Gd I, for which a progress report will be given.

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[1]Den Hartog, E A, Chisholm, J P, and Lawler, J E, accepted for publication, J. Phys B, June 2010.

Radiative Parameters of Nb I Excited States

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Radiative parameters of atoms and ions are generally important data for plasma physics and astrophysics. Niobium is of particular interest since, as a highly refractory metal, it is included in the inner walls of fusion devices. Niobium has also been discovered in heavy-element stars like the M-type long period variable (LPV) Mira and MS-type LPV, χ Cyg [1].

In the present work radiative lifetimes of 17 excited levels in Nb I (5p y $^6D°_{9/2}$, 5p x $^6D°_{7/2}$, 5p w $^4G°_{7/2,9/2,11/2}$, 5s5p v $^4D°_{1/2,3/2,5/2,7/2}$, 5s6p n $^4D°_{1/2,3/2,5/2,7/2}$, 5s6p o $^4F°_{3/2,5/2,7/2,9/2}$) are reported. They were measured with the time-resolved laser-induced fluorescence (TRLIF) technique. The investigated levels in Nb I, were excited in a single-step process from the ground term ($4d^4 5s$ a ^6D) or from the low-lying $4d^3 5s^2$ a ^4F term.

Free Nb atoms were created in a laser-produced plasma by focusing a 10 Hz frequency doubled Nd:YAG laser onto a rotating target, placed inside a vacuum chamber with a pressure of 10^{-5} mbar. The atoms were then selectively excited by crossing the ablation plasma 1 cm above the target with a (typically) 1.2 ns duration pulse from a dye laser pumped by a Nd:YAG laser. Further details of the experimental setup can be found in [2]. For 15 of the investigated levels the lifetimes have been measured for the first time. In addition, we have also performed a theoretical investigation using the Hartree – Fock multiconfigurational technique.

This work was financially supported by the Integrated Initiative of Infrastructure Project LASERLAB-EUROPE, contract RII3-CT_2003-506350, the Swedish Research Council through the Linnaeus grant, the Knut and Alice Wallenberg Foundation. NSF of Bulgaria is acknowledged for financial support (grant DO 02-274/2008). Financial support from the belgian FRS-FNRS is also acknowledged.

[1] G. Wallerstein, J. F. Dominy, Astrophys. J. **330**, 937-941 (1988).

[2] G. Malcheva *et al*. Mon. Not. R. Astron. Soc. **395** 1523 (2009).

Lifetimes and Branching Fractions for Ultraviolet Transitions in P II

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We describe our ongoing studies on ultraviolet transitions in P II that are needed for precise determinations of the phosphorus abundances in interstellar material. These abundances provide information on the amount of phosphorus incorporated into grains in nearby diffuse clouds and on the synthesis of phosphorus nuclei in distant galaxies. Our initial study (Federman et al. 2007) of the multiplet at 1154 Å ($3s^23p^2$ ^3P – $3s^23p4s$ $^3P^o$) yielded the most precise experimental oscillator strengths to date from measured lifetimes and branching fractions. The branching fractions, which differ slightly from LS coupling rules, are in excellent agreement with large scale theoretical computations and with a semi-empirical analysis based on intermediate coupling amplitudes deduced from experimental energy level data (Curtis 2000).

We are now examining transitions with upper levels involving the $3s3p^3$ and $3s^23p3d$ configurations (multiplets at 1308, 967, and 964 Å). Lifetimes and branching fractions for the $J = 1$ and 2 levels of the $3s3p^3$ $^3P^o$ term will be presented, along with previous results for the multiplet λ1308. We will also describe our attempts to extend the semi-empirical method for branching fractions to cases where configuration interaction (CI) is not negligible. In particular, we are considering CI between the $3s3p^3$ and $3s^23p3d$ configurations as well as intermediate coupling caused by spin-orbit interactions within those multiplets and also within the $3s^23p^2$ configuration.

[1] S.R. Federman, M. Brown, S. Torok, S. Cheng, R.E. Irving, R.M. Schectman, and L.J. Curtis, Ap. J., **660**, 919-921 (2007)
[2] L.J. Curtis, J. Phys. B, **33**, L259-L263 (2000)

Effective Collision Strengths for Transitions within the Ground Configuration of carbon-like Neon

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Accurate data for electron-impact excitation of Ne V are of significant importance to the analysis of infrared spectrum of astrophysical plasmas like planetary nebulae or active galactic nuclei. From Infrared Space Observatory (ISO) observations of Ne V lines at 14.3 μm ($2s^2 2p^2\ ^2P_1 - ^2P_2$) and 24.3 μm ($2s^2 2p^2\ ^2P_0 - ^2P_1$) in planetary nebulae, Rubin *et al.* ([1], [2]) found line flux ratios F(14.3)/F(24.3) below the low-electron density (N_e) theoretical limit. These results could mean that the collision strengths for these lines may need revision.

We thus report on the calculation of new electron collision strengths for transitions within the $1s^2 2s^2 2p^2\ ^3P$ ground term of Ne V. This extensive close-coupling calculation was performed using the Dirac Atomic R-matrix Codes (DARC). The present collision strengths were integrated over a Maxwellian distribution of electron energies. The resulting effective collision strengths are given for a range of temperatures around 10,000 K, which are typical of photoionized nebulae, and compared with previous results available in the literature ([3], [4]). These 'low' temperature collision strengths were found to be affected by resonances close to the threshold whose positions are likely to be very uncertain.

[1] R. H. Rubin *et al.*, ASP Conference Series **247**, 479-498 (2001)
[2] R. H. Rubin *et al.*, IAU Symposium Series **217**, 190 (2004)
[3] D. J. Lennon and V. M. Burke, Astron. Astrophys. Suppl. Ser. **103**, 273 (1994)
[4] D. C. Griffin and N.R. Badnell, J. Phys. B: At. Mol. Opt. Phys. **33**, 4389-4408 (2000)

A New, Greatly Expanded Tabulation of Accurate Transition Probabilities for the Lightest Five Elements

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We have completed extensive compilations of atomic transition probabilities for hydrogen and its isotopes, and for the spectra of helium, and lithium,[1] as well as for beryllium and boron.[2] For hydrogen and helium as well as for hydrogen-like and helium-like spectra, the data are exact to within at least five significant figures. For hydrogen and its isotopes, fully relativistic calculations were carried out that agree with earlier non-relativistic results within the first four digits or better. The tabulated data for Li I, Be I, and B I and their lower ions are from sophisticated atomic structure calculations, and most results are available in the dipole-length and dipole-velocity representations. They usually agree within 1%, but for weaker lines of beryllium and boron, larger differences are encountered, up to 65% between the two formalisms. A few comparisons with experimental lifetime data are available, involving strong lines of Li I, Be I and B I. They show excellent agreement. Our new tabulations supersede the earlier NBS tables of the 1960s and are greatly expanded. For example, the new tables for He I contain 2,400 transitions, while the earlier tables contained only 130. Likewise, the new tables for Be and B comprise 1,400 lines, while the earlier ones contain less than 100, and their quality was estimated to be much lower. The new tabulations have been made part of the NIST Atomic Spectra Database (ASD).[3]

[1] W. L. Wiese and J. R. Fuhr, J. Phys. Chem. Ref. Data **38**, 565-719 (2009)
[2] J. R. Fuhr and W. L. Wiese, J. Phys. Chem. Ref. Data **39**, 013101 (2010)
[3] Yu. Ralchenko, A. E. Kramida, J. Reader, and NIST ASD Team (2010). *NIST Atomic Spectra Database* (version 3), [Online]. Available: http://physics.nist.gov/asd

The FERRUM project: Laboratory-measured transition probabilities for Cr II

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Transition probabilities for 145 allowed Cr II lines corresponding to radiative decays from the $z\,^4\mathrm{H}_J$, $z\,^2\mathrm{D}_J$, $y\,^4\mathrm{F}_J$ and $y\,^4\mathrm{G}_J$ levels with energies between 63000 and 68000 cm^{-1} have been experimentally determined using a combination of lifetime and branching fraction (*BF*) measurements.

The lifetimes were measured by monitoring time resolved laser induced fluorescence [1] at the Lund High Power Laser Facility and *BF*s were determined by line fitting of an intensity calibrated Fourier transform spectrum from a Penning discharge lamp with chromium cathodes recorded at Lund Observatory.

The log(*gf*)-values were compared with results from the semi-empirical calculations of Kurucz [2] and Raasen & Uylings [3]. Several of the investigated upper levels are close in energy and appear to be severely mixed which complicates the calculations. Nevertheless, the experimental A-values are reasonably well reproduced by the calculations of Raasen & Uylings [3] which also show great agreement with our experimental lifetimes.

[1] H. L. Xu, S. Svanberg, P. Quniet, H. P. Garnir and E. Biémont, J. Phys. B **36**, 4773 (2003)
[2] R. L. Kurucz, Trans. IAU, XXB, M. McNally, Ed., (Dordrecht: Kluwer) 168 (1988)
[3] A. J. J. Raasen and P. H. M. Uylings, unpublished data available at: ftp://ftp.wins.uva.nl/pub/orth/chromium

F-dependent lifetimes and intensity redistribution due to off-diagonal hyperfine interaction

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We present a theoretical investigation of the hyperfine structure of the $5s5d\ ^3D_2\ -\ 5s4f\ ^3F^o_{2,3}$ transitions in In II, Grumer *et al.* [1]. Karlsson and Litzén [2] failed in determining hyperfine constants for the upper levels of theses transitions. We show that this is dues to strong off-diagonal hyperfine interaction, which not only changes the position of the individual hyperfine lines but also introduces large intensity redistribution among the different hyperfine levels.

A similar case has earlier been investigated by Andersson *et al.* [3]. In this paper it was shown that the structure of the $4s4d\ ^3D_2\ -\ 4s4f\ ^3F^o_{2,3}$ transitions in Ga II were very sensitive to off-diagonal hyperfine interaction and the experimental spectrum by Karlsson and Litzén [4] was reproduced to high accuracy. Based on methods developed for the Ga II project (Andersson *et al.* [3]), two programs, HFSMIX and HFSTRANS, were developed by Grumer and Andersson [5]. Using these, the experimental spectrum of the $5s5d\ ^3D_2\ -\ 5s4f\ ^3F^o_{2,3}$ transitions in In II by Karlsson and Litzén [2] could be reproduced to high accuracy in Grumer *et al.* [1].

We present hyperfine dependent gf-values and show that off-diagonal hyperfine interaction reduces some of the gf-values by two orders of magnitude, while others are increased by up to more than a factor of 6. We also discuss the influence on the hyperfine structure of an accurate representation of the level-splitting of the $5s4f$ configuration. We show that the hyperfine interaction in $^3F^o_3$ and $^1F^o_3$ is very hard to determine accurately even in a large-scale calculation, and we derive a semi-empirical method for adjusting our results using an experimentally known, diagonal hyperfine constant for $5s4f\ ^1F^o_3$. The resulting theoretical synthetic spectra reproduce the experimental one by Karlsson and Litzén [2] to very high accuracy and facilitate the identification of all observed lines.

References

[1] J. Grumer, M. Andersson and T. Brage, J. Phys. B **43**, 074012 (2010).

[2] H. Karlsson and U. Litzén, J. Phys. B. **33**, 2929 (2000).

[3] H. Karlsson and U. Litzén, J. Phys. B. **34**, 4475 (2001).

[4] M. Andersson, P. Jönsson and H. Sabel, J. Phys. B **39** 4239 (2006).

[5] J. Grumer and M. Andersson *unpublished*

Accurate configuration-interaction calculation of transitions in Sn II

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Atomic structure data pertaining to singly-ionised tin is of particular relevance in astrophysical and fusion research applications. The strong $5p\ ^2P^o_{1/2} - 5d\ ^2D_{3/2}$ transition at 1400.45Å has been adopted by Sofia *et al* [1] in their determination of the interstellar gas-phase abundance of tin, while the transitions found at 5334Å ($6p\ ^2P^o_{1/2} - 6d\ ^2D_{3/2}$), 5563Å ($6p\ ^2P^o_{3/2} - 6d\ ^2D_{5/2}$) and 5591Å ($5d\ ^2D_{3/2} - 4f\ ^2F_{7/2}$) have been highlighted by Foster *et al* [2] as representing suitable candidates for diagnostic purposes in the plasmas found in fusion power plants.

In response to the large inconsistencies that persist among and between previous theoretical and experimental work for these transitions, involving levels of the problematic, heavily-mixed ^{2}D *LS* term, we have undertaken an extensive configuration-interaction (CI) calculation using the general atomic structure package CIV3 [3, 4]. We will present our sequential determinations of the oscillator strengths (OS), (in the *LS* coupling scheme), as the complexity of our theoretical model was increased, demonstrating that the consistent inclusion of all important valence and core-valence effects was imperative in achieving results that not only converged, but converged to the 'correct' values. Paying particular attention to the $5s5p^2 - 5s^25d\ ^2D$ interaction, our *ab initio* calculation has reproduced the experimental ^{2}D energy separations to within 1%, permitting the final minor corrections to the CI coefficients to be made by application of our customary 'fine-tuning' technique.

As expected, our final Breit-Pauli OS exhibit marked discrepancies with previous theoretical models based on limited CI expansions. We would argue that our calculation, being of a much larger scale, corresponds to a major improvement, (a claim validated by the extensive checks to which we have subjected our results, consistent with estimated uncertainties in the region of 5% for the stronger transitions), achieving an accuracy required for the proposed applications. On the experimental front, the consistency between our results and the greater part of the published measurements is a further indication of the reliability of our model, and where larger disparities do exist our calculations are supported by an independent theoretical investigation.

[1] Sofia U J, Meyer D M and Cardelli J A 1999 *Astrophys. J.* **522** L137
[2] Foster A R, Counsell G F and Summers H P 2007 *J. Nucl. Mater.* **363-365** 152
[3] Hibbert A 1975 *Comput. Phys. Commun.* **9** 141
[4] Glass R and Hibbert A 1978 *Comput. Phys. Commun.* **16** 19

The utility of atomic lines in cool dwarfs

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The detectable features in the atmospheres of cool dwarf stars change rapidly from atoms to molecules as the temperature decreases. Although a few molecular opacities are relatively well determined most are not. This is particularly true shortward of 2 microns where the peak of the spectral energy distribution lies. This leads to the rather limited predictive power of models and a large range of temperatures and metallicities being presented in the literature. An alternative route to probe their atmospheres is to consider atomic lines. Although relatively weak, atomic lines are well distributed across the peak of the energy distribution. We consider the potential for multi-wavelength analysis of a number of atomic lines as a probe of their atmospheric properties of cool stars from M dwarfs to L dwarfs.
Preliminary results indicate that abundances of elements and/or model structures might be derived for cool stars to within a few percent with suitable observational data.

Improved log(gf) Values of Selected Lines in Mn I and Mn II for Studies of Non-Equilibrium Effects in Stellar Photospheres

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Significant improvements in oscillator strengths (f-values) for first- and second-spectra lines of most elements have substantially increased the accuracy and precision of elemental abundance studies. Classic models of stellar photospheres are based on local thermodynamic equilibrium (LTE) and one dimensional (1D) approximations. At this time non-LTE/3D effects have become more of a concern [e.g. 1]. A study of Fe-group abundance values as a function of stellar metallicity (or age) is an interesting case where observed trends are unexplained [2, 3]. These trends may be due to some combination of residual errors in f-values, non-LTE/3D photospheric effects, and/or poorly understood nuclear physics. To help explain these trends we are returning our focus to the Fe-group atoms and ions with the goal of shrinking the overall uncertainties on selected sets of f-values. This work presents transition probabilities with very low uncertainties for a selected set of multiplets of Mn I and Mn II. Multiplets are chosen which are accessible to ground-based observations, are relatively unblended and unsaturated in stellar spectra, and which are amenable to accurate branching fraction determination. We report on new radiative lifetime measurements for 22 levels of Mn I from the e^8D, z^6P, z^6D, z^4F, e^8S and e^6S multiplets and 3 levels of Mn II from the z^5P multiplet using time-resolved laser-induced fluorescence on a slow atomic beam. New branching fractions for transitions from these levels, measured using a Fourier-transform spectrometer, are also reported. When combined, these measurements yield transition probabilities for 47 transitions of Mn I and 12 transitions of Mn II. Comparisons are made to data from the literature and to simple Russell-Saunders or LS theory. Final recommended values, which are weighted averages of all available modern measurements and in some cases LS theory, are given for the transition probabilities. These recommended log(gf) values are accurate to +/- 0.02 dex with high (~2 sigma) confidence. These lab measurements provide a foundation for studies of non-LTE/3D effects in stellar photospheres.

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[1] M. Asplund, "New Light on Stellar Abundance Analyses: Departures from LTE and Homogeneity", Ann. Rev. Astron. Astrophys. **43**, 481-530 (2005).
[2] A. McWilliam, G. W. Preston, C. Sneden, & L. Searle, "Spectroscopic Analysis of 33 of the Most Metal Poor Stars.II" Astron. J. **109**, 2757-2799 (1995).
[3] R. Cayrel, E. Depagne, M. Spite, V. Hill, F. Spite, P. François, B. Plez, T. Beers, F. Primas, J. Andersen, B. Barbuy, P. Bonifacio, P. Molaro & B. Nordström, "First stars V - Abundance patterns from C to Zn and supernova yields in the early Galaxy", Astron. & Astrophys. 416, 1117-1138 (2004).

Lifetime measurements for atomic levels with astrophysical interest

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Lifetimes are measured at the Lund High Power Laser Facility, Sweden, using the time resolved laser induced fluorescence technique [1], [2] and [3]. Atoms are pumped from low levels and the decay fluorescence is detected as a function of time.

The basic experimental set up has been used for many years but it has been improved and developed continuously to meet the demands of new astrophysical atomic physics challenges.

We describe the method and present new measurements in the spectrum of neutral antimony (Sb I).

[1] H. Bergström H. Faris, G.W. Hallstadius, H. Lundberg, A Persson, and C.G. Wahlström, Z. Phys. D 8, 17 (1988).

[2] H.L. Xu, S. Svanberg, P. Quinet, H.P. Garnir, and É. Biémont, J. Phys. B: At. Mol. Opt. Phys. 36, 4773 (2003).

[3] H.L. Xu, A. Persson, S. Svanberg, K. Blagoev, G. Malcheva, V. Pentchev, É. Biémont, J. Campos, M. Ortiz, and R. Mayo, Phys. Rev. A 70, 042508 (2004).

Relativistic Corrections to He I Transition Rates

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The relativistic corrections to the theoretical oscillator strengths of light elements such as helium are typically less than 0.1% and usually are ignored. However, they can be important for comparisons with the most accurate experiments, and they rapidly increase in magnitude with increasing nuclear charge. We have begun with the spin-forbidden electric-dipole transitions of neutral helium using calculations of 1) extremely accurate wavefunctions without relativistic corrections, 2) spin-permitted matrix elements using the nonrelativistic infinite-mass wavefunctions, 3) spin-changing matrix elements through the perturbations of the wavefunctions by the spin-orbit and spin-other-orbit Breit operators, 4) the use of pseudo states in the sums over all the intermediate states including the continuum, and 5) the inclusion as perturbers of the $^1S_0$ and $^3S_1$ states the pseudo states corresponding to the doubly excited 2p2p' $^3P^e_0$ and 2p3p' $^1P^e_1$ terms respectively. As examples of these calculations we present oscillator strengths for the transitions $1\ ^1S_0$ - $2\ ^3P_1$, $2\ ^1S_0$ - $2\ ^3P_1$, $2\ ^3S_1$ - $2\ ^1P_1$, $2\ ^1P_1$ - $3\ ^3D_{1,2}$ and $2\ ^3P_{1,2}$ - $3\ ^1D_2$.

Spectral data for nickel: Ni I through Ni VIII

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A critical compilation of spectral data for neutral nickel and its first seven ions is in progress. Large extensions of energy level and wavelength data for nickel have been produced in several laboratories since the compilation of energy levels by Sugar and Corliss in 1985 [1]. The later compilation by Shirai et al. [2] includes spectral data only for highly ionized atoms: Ni IX-Ni XXVIII. No compilations of wavelengths have been made for Ni I-Ni VIII.

In our compilation we consider only publications that give data for observed lines. For each ion, we combine lines measured in different ranges into a single unified line list. If lines are measured by more than one author, we select those that have the lower uncertainties. Whenever authors provide energy levels, we verify the consistency of observed wavelengths with the values calculated from the energy levels (Ritz values). To obtain the best energy levels, we use the level optimization code LOPT described in [3].

Final results will be presented in two types of tables for each ion from Ni I to Ni VIII. Tables of lines contain observed wavelengths, uncertainties of observed wavelengths, intensities of lines, wavenumbers, classifications of transitions including configurations, terms and J values for lower (i) and upper (k) levels, and references to the sources of lines. For neutral and singly ionized nickel, we also provide transition probabilities A_{ki}, uncertainties of A_{ki}, and references to the sources. Tables of energy levels contain energy levels, their uncertainties, designations, and where available, leading percentages of the eigenvectors. For each spectrum we also give the ionization energy and provide brief discussions. We plan to incorporate these new results in the NIST Atomic Spectra Database to supplement the nickel data already accessible there.

[1] J. Sugar and C. Corliss, J. Phys. Chem. Ref. Data, **14**, Suppl. 2, 664 pp. (1985)
[2] T. Shirai, J. Sugar, A. Musgrove and W. L. Wiese, J. Phys. Chem. Ref. Data, Monograph No. 8, AIP Press, Melville, NY, 632 pp. (2000)
[3] A. E. Kramida and G. Nave, Eur. Phys. J. D **37**, 1 (2006)

Measurements of isotope shifts and hyperfine structure in Ti II

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Titanium contributes enormously to stellar spectra. In the Sun it is in third place in terms of numbers of lines, and in B, A and F stars the first ions of Fe, Cr and Ti dominate the visible spectrum. Studies of the enhanced abundances of α elements such as Ti compared to Fe-group elements in metal-poor stars are a window into the history of chemical evolution in the early Universe. In particular, one can observe the effects on nucleosynthesis of the time delay between Types II and Ia supernovae. Chemical abundances of Ti derived from Ti II are generally considered more reliable than those from Ti I as a result of smaller non-LTE effects.

Modern measurements of chemical abundances by stellar spectral synthesis techniques make use of atomic physics data on isotope shifts (IS), hyperfine structure (hfs), and other heterogeneous line-splitting effects to correct properly for saturation. Also, the transition elements have interleaved $3d^3$, $3d^2\,4s$, and $3d\,4s^2$ configurations, resulting in strong configuration interaction (CI) effects. Since IS and hfs parameters are sensitive probes of CI, experimental measurements provide a significant but not intractable theoretical challenge for many-body atomic structure calculations.

We have applied fast-ion-beam laser-fluorescence spectroscopy to measure the IS of 38 transitions in the wavelength range 429-457 nm and the hfs of 22 levels in Ti II. The isotope shift and hyperfine structure measurements are the first for these transitions and levels.

Accurate laboratory wavelengths of the 1910 Å TiII resonance transitions relevant to time variations of the fine structure constant

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High-redshift quasi-stellar object (QSO) absorption spectra provide an ideal means of probing possible space-time variations in the fine-structure constant (α). Any changes in α would manifest themselves through small changes in the expected position of absorption lines, and thus their detection relies heavily on the availability of highly accurate rest-frame wavelengths[1].

Here, we present the results of high-precision laboratory wavelength measurements, conducted on the Imperial College vacuum-ultraviolet (VUV) Fourier transform spectrometer (FTS), to study the Ti II resonance transitions seen at 1910 Å in the emission of a Ti hollow-cathode light source. These lines have been identified as being of high importance to the analysis of QSO data[2].

In addition to accurate absolute Ti wavelengths, we provide calibrated wavelengths to important Mg and Zn transitions. These were obtained at the same time as the Ti wavelengths by inserting fragments of Mg and Zn into the Ti cathode, thus maximising the accuracy of all three sets of lines in relation to one another.

The resulting composite spectra were calibrated with respect to the established[3] Ar II standard lines[4] (obtained from the lamp carrier gas), and also with respect to Mg wavelengths found independently from laser frequency-comb measurements[5][6]. Both gave Ti II wavelengths in agreement with the other, providing confirmation of the reliability of the Ar II standard. However, whilst the Ar II calibration was accurate to 0.16 mÅ (0.004 cm^{-1}), the Mg frequency-comb calibration (which was more directly applicable to the VUV region) increased the accuracy to 0.05 mÅ (0.002 cm^{-1}). Wavelengths for the Mg and Zn transitions agreed with those published previously[7][8].

[1] J. K. Webb et al., Phys. Rev. Lett. **82**, 884 (1999)
[2] J. C. Berengut et al., Mem. S. A. It. **80**, 795 (2009)
[3] R. C. M. Learner and A. P Thorne, J. Opt. Soc. Am. B **5**, 2045 (1988)
[4] W. Whaling et al., J. Quant. Spectrosc. Radiat. Transfer **53**, 1 (1995)
[5] S. Hannemann et al., Phys. Rev. A **74**, 012505 (2006)
[6] E. J. Salumbides et al., Mon. Not. R. Astron. Soc. **373**, L41 (2006)
[7] M. Aldenius et al., Mon. Not. R. Astron. Soc. **370**, 444 (2006)
[8] J. C. Pickering et al., Mon. Not. R. Astron. Soc. **300**, 131 (1998)

Excitation energies, E1, M1, and E2 transition rates, lifetimes, and polarizabilities in Ca^+, Sr^+, Cd^+, Ba^+, and Hg^+ ions

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Excitation energies of the $ns_{1/2}$, np_j and nd_j states in Cd^+ (n=5), Hg^+ (n=6) and $ns_{1/2}$, np_j and $(n-1)d_j$ states in Ca^+ (n=4), Sr+ (n=5), and Ba+ (n=6) are evaluated. First-, second-, third-order, and all-order Coulomb energies and first- and second-order Coulomb-Breit energies are calculated.

Reduced matrix elements, oscillator strengths, and transition rates are determined for the $ns_{1/2}$ - np_j -nd_j, and $ns_{1/2}$ -np_j -$(n-1)d_j$, possible electric-dipole transitions in Cd^+ (n=5), Hg^+ (n=6) and in Ca^+ (n=4), Sr^+ (n=5), and Ba^+ (n=6), respectively. Electric-quadrupole matrix elements are evaluated to obtain $ns_{1/2}$ - $(n-1)d_j$ transition rates in Ca^+ (n=5), Sr^+ (n=5), and Ba^+ (n=6). The matrix elements are calculated using both relativistic many-body perturbation theory, complete through third order, and the relativistic all-order method restricted to single and double (SD) excitations.

The SD lifetime results for the np_j and nd_j states in Cd^+ (n=5), Hg^+ (n=6) and np_j and $(n-1)d_j$ states in Ca^+ (n=4), Sr^+ (n=5), and Ba^+ (n=6) are compared with the latest available experimental measurements. The contributions of magnetic-dipole $nd_{3/2}$-$nd_{5/2}$ transition to the lifetimes of the $nd_{5/2}$ level in Ca^+ (n=4), Sr^+ (n=5), and Ba^+ (n=6) ions are discussed.

Scalar polarizabilities of the $ns_{1/2}$, np_j and nd_j states, and tensor polarizabilities of the $np_{3/2}$ and nd_j excited states of Ca^+, Sr^+, and Ba^+ are evaluated. These calculations provide a theoretical benchmark for comparison with experiment and theory.

Oscillator Strengths for Transitions in Singly Ionized Nitrogen

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A number of strong features due to N II have been observed in the emission spectra of Titan's upper atmosphere and Saturn's inner magnetosphere. Accurate radiative transition probabilities of N II are needed to achieve good fits to high-resolution observations from Cassini. The multiconfiguration Hartree-Fock method [1] with term-dependent non-orthogonal orbitals is employed for an accurate representation of wave functions in singly ionized nitrogen. Extensive configuration-interaction wave functions have been used to calculate line strengths, oscillator strengths, and transition probabilities for dipole-allowed, intercombination, and forbidden transitions among the fine-structure levels of the $2s^22p^2$, $2s2p^3$, $2s^22pnl$ (n = 3-4; l = 0-2), and $2s2p^23s$ configurations. The levels have been accurately represented by using both spectroscopic and correlation radial functions. The wave functions exhibit large correlation corrections and significant term-dependence of one-electron valence orbitals. Several sets of correlation orbitals nl (l = 0-4) were generated for the various even and odd parity levels. The relativistic corrections are included through the one-body and two-body operators in the Breit-Pauli Hamiltonian.

Progressively larger calculations are performed to check for important electron correlation contributions and for convergence of results. The calculated excitation energies of the levels show very close agreement with experiment. The accuracy of the results is evaluated by the agreement between the length and velocity formulations of oscillator strengths combined with the agreement between the calculated and measured transition energies. Our results are compared with previous calculations and experimental measurements. The calculated lifetime for the $2s2p^3\,{}^5S^o_2$ metastable level shows good agreement with the latest experimental results using a heavy-ion storage ring [2]. The intercombination transitions usually occur due to small components in the total wave function; therefore they are very sensitive to the approximation used.

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[1] C. Froese Fischer, Comput. Phys. Commun., **176**, 559 (2007)

[2] E. Träbert, A. Wolf, E. H. Pinnington, et al., Phys. Rev. A, **58**, 4449 (1998)

Investigation of tungsten impurity spectra at the LHD

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Abstract:

We have measured extreme ultraviolet (EUV) spectra from highly charged tungsten ions in low density and high temperature plasmas produced in the Large Helical Device at the National Institute for Fusion Science. The EUV spectra emitted after injection of a tungsten pellet into a hydrogen plasma were recorded at plasma temperatures of 1.5 and 3 keV. Both spectra were dominated by an intense transition array in the 4.5 – 6.5 nm region, the profile and extent of which was different in both spectra. Some discrete lines present in both were identified by comparison with existing spectral data, in particular the 4d-4f transitions in Ag like and Pd like W XXVIII and XXIX were present in both spectra [1]. Atomic structure calculations with the Cowan code [2] showed that the dominant emission in both spectra arose from $\delta n = 0$, $n = 4 - n = 4$ transitions and the differences could be attributed to the appearance of 4p- 4d transitions from W XXXIX – W XLV in the higher temperature spectrum. Wavelengths and gA values for resonance transitions for W ions with open 4f, 4d and 4p subshells were obtained. We also investigated if the effect of low density favours transitions from states accessible primarily from the lowest level in line with recently reported results.

[1] J. Sugar, V. Kaufman and W.L. Rowan 1993 J. Opt. Soc. Am. **B10** 1977

[2] R. D. Cowan 1981 *The Theory of Atomic Structure and Spectra* (University of California Press, Berkeley)

Spectra of moderately charged tungsten ions

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In relation with the ITER project and some other tokamaks using tungsten as material for divertor, the determination of radiative properties of all ionization stages of this atom is of current interest. Our purpose is to extend the knowledge on moderately charged ions (W III-W X) by analysing high resolution spectra of these ions. The recent compilation of existing data [1] will serve as the starting point.

For observation of resonance lines of W VI - W X, a set of spectra was produced in the wavelength region of 150-350 Å using a triggered spark source and recorded on photographic plates with a grazing incidence spectrograph (resolution ~0.015 Å) in the Institute of Spectroscopy of Troitsk. The vacuum spark spectrum in this region consists of about 3000 lines. The most intense lines are located in two regions centred at about 220 and 250 Å. They are composed, apart from known W VII lines [2], predominantly by the unknown ($4f^{14}5s^{2}5p^{k}$ + $4f^{13}5s^{2}5p^{k+1}$) - [$4f^{14}5s5p^{k+1}$ + $4f^{14}5s_{2}5p^{k-1}$(5d+6s) + $4f^{13}5s^{2}5p^{k}$(5d+6s)] transitions in W VIII – W X spectra (k=5-3, respectively).

For longer wavelength region (500-1650 Å) where transitions between excited states occur, spectra were produced by sliding spark and triggered spark sources and recorded on photographic plates for precise wavelength measurement and on image plates for intensity measurements with the 10 m normal incidence spectrograph (res. ~0.008 Å) in Meudon.

Theoretical calculations have been performed by means of the Cowan codes, predicting level energies and transition probabilities that take into account configuration interactions. Parametric study allows the continuous improvement of these predictions by least squares fit of radial integrals against experimental level energies. Analyses of the spectra are in progress.

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[1] A. E. Kramida, T. Shirai, At. Data Nucl. Data Tab. **95**, 305-474 (2009)
[2] J. Sugar, V. Kaufman, Phys. Rev. A **12**, 994-1012 (1975)

Creation, destruction, and transfer of atomic multipole moments by electron scattering: relativistic treatment

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In previous work [1], cross sections for the creation, destruction, and transfer of atomic multipole moments by electron scattering have been defined using the wave-packet propagation scheme along with density-matrix techniques. In that work, the Hamiltonian was assumed to have been non-relativistic with some relativistic corrections. The development of a definition for the above cross sections was mainly motivated by the need for their use in modeling anisotropic plasmas. There are, however, plasma conditions for which a fully relativistic treatment is warranted. Furthermore, a fully relativistic, convergent close coupling code has been recently developed and implemented at Curtin University for the description of electron scattering from atoms and ions [2]. The purpose of this work is the development of a formal definition for those cross sections under relativistic conditions. Consequently, in this work we shall use the Dirac equation and associated many-electron relativistic Hamiltonian. While for many-electron systems there is no single relativistic Hamiltonian, some such Hamiltonians have been used in the past for bound-state and scattering calculations that contain effective potentials. In the previous work mentioned above [1], the wave-packet formulation has been used. Altnernatively, it is possible to formulate collision physics on an equivalent basis by defining the asymptotic values of the time development operator via a regularization procedure [3] that makes the formalism convenient to handle in conjunction with plane-wave initial states. It is this formalism that we shall use here in order to define the above cross sections under relativistic conditions.

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[1] G. Csanak, D. P. Kilcrease, D. V. Fursa and I. Bray, Phys. Rev. A **78** 062716 (2008)

[2] D. V. Fursa and I. Bray, Phys. Rev. Lett. **100** 113201 (2008)

[3] M. Gell-Mann and M .L. Goldberger, Phys. Rev. **91** 398 (1953)

Abstract submitted for The 10th International Colloquium on Atomic Spectra and Oscillator Strengths (ASOS) for Astrophysical and Laboratory Plasmas, Berkeley, California
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Polarized Atomic Radiative Emission in Electric and Magnetic Fields*

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A reduced-density-matrix approach is employed to provide a general theoretical description of polarized radiative emission during single-photon transitions from bound and autoionizing states of many-electron atomic systems in the presence of a general arrangement of static (or quasi-static) electric and magnetic fields. Polarized radiative emission from partially ionized atomic systems in plasmas can occur as a result of the excitation of the radiating atomic states by electrons or ions with an anisotropic velocity distribution, which can be produced in an electron or ion beam experiment, in a non-equilibrium plasma environment, and in an electromagnetic field that is sufficiently intense in the relevant spectral region. Polarized radiative emission can also be produced or modified during the excitation of the atomic system in the presence of electric and magnetic fields, and electromagnetic fields. In electric and magnetic fields, the normally overlapping angular-momentum-projection components of atomic spectral lines can be substantially shifted from their field-free positions and split into spectroscopically resolvable (and inherently polarized) features. Due to the breakdown of the field-free angular-momentum and parity selection rules, otherwise forbidden components of atomic spectral lines can be generated. Using a representation based on the field-free many-electron atomic states, the Stark-Zeeman patterns are determined by a diagonalization of the atomic Hamiltonian in the presence of electric and magnetic fields. In the density-operator approach, account can be taken of the coherent excitation of a particular subspace of the initial atomic bound or autoionizing states. A general expression for the matrix elements of the detected-photon density operator provides a unified framework for the analysis of the spectral intensity, angular distribution, and polarization of the Stark-Zeeman patterns. From a unified development of time-domain (equation-of-motion) and frequency-domain (resolvent-operator) formulations of the more comprehensive reduced-density-matrix approach, the non-equilibrium atomic-state kinetics and the homogeneous spectral-line shapes can be systematically and self-consistently described.

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DOUBLE POLARIZED dd-FUSION

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A double-polarized dd-fusion experiment is under preparation at PNPI, Gatchina. The experimental program includes the measurements of the asymmetry in the differential cross section of the reactions $d+d\rightarrow{}^3He+n$ and $d+d\rightarrow t+p$. The total cross section modification for polarized dd-fusion will also be investigated. Increase by a factor of 1.5 was already deduced for the $d+{}^3He$ (see e.g. [1]) and the d+t reactions. The experiment is supported by ISTC (project 3881) and DFG (project EN 902/1-1).

The spin-correlation coefficients $C_{z,z}$ and $C_{zz,zz}$ will be measured to determine the quintet-state suppression factor for both reactions, which has quite different theoretical predictions [2] and is very important for the building of neutron-lean fusion reactor. But the question remains: will it persistence the Polarization in a Fusion Process? This question can be answered by doing the measurements proposed in experiment [3].

The experimental setup for double-polarized measurements consists of two polarized sources, a detector system and polarimeters for the polarization measurements. The polarized-atomic beam source (ABS) from the former SAPIS experiment [4] at IKP of the University of Cologne was sent to PNPI to be used as a polarized deuterium jet target. It is also equipped with the essential parts of the Cologne Lamb-shift polarimeter (LSP). All the equipment has to be refurbished and updated for the deuterium beam. The polarized deuteron beam will be produced by the polarized ion source POLIS from KVI, Groningen [5], which will be sent to PNPI in the spring of 2010 along with the LSP. The expected target density of $2\cdot10^{11}$ at/cm^2 and an ion beam of ~ 20μA will provide a luminosity of $3\cdot10^{25}$ cm^{-1}s^{-1}. This will result in 2 months of beam time for the quintet-state suppression factor at 30 keV. The polarization of the ion beam and the jet target will be measured with the LSPs. A nuclear-reaction polarimeter will also be used for the ion beam. A silicon PIN-photodiodes will be arranged to the 4π-detector system.

In addition, more spin-correlation coefficients can be measured at different energies with this experimental setup, to get more information about the dd-fusion process. The screening effect due to atomic electrons which shows up in the astrophysical S-factor [6] may also be investigated in this experiment for different spin combinations of the electron and nucleus.

1. Ch. Leemann et al. , Helv. Phys. Acta 44, 141 (1971).
2. H. Paetz gen. Schieck. The status of “Polarised Fusion”, review, accepted by The European Physical Journal A (EPJ A).
3. J.-P. Didelez and C.Deutsch //19-th International IUPAP Conference on Few-Body problem in Physics.
4. R. Emmerich and H. Paetz gen. Schieck, NIM A586, 387 (2008).
5. H.R. Kremers et al., NIM A536, 329 (2005).
6. F. Raiola et al., Eur. Phys. J. A13, 377 (2002).

Theoretical predictions for plasma polarization spectroscopy experiments at the Zebra generator at UNR

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Polarization-sensitive experiments with Ti and Mo X-pinches on Zebra at UNR have provided the experimental evidence of the existence of anisotropy in Z-pinch plasmas in the form of electron beams [1]. They motivate the further development of such diagnostics and in particular the search for the new x-ray lines that help to make it a reliable diagnostic tool. This work overviews our previous calculations of linear polarization of diagnostically important x-ray lines [2]. It also presents the new theoretical predictions of polarization properties of other K- and L-shell lines that can be potential candidates for such diagnostics. The calculations of atomic characteristic and polarization data are performed using the FAC code developed by M.F. Gu. The depolarization effects in plasmas are also discussed.

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[1] A.S. Safronova, V.L. Kantsyrev, P. Neill *et al*, Can. J. Phys. **86**, 267-276 (2008)
[2] A. S. Shlyaptseva, V.L. Kantsyrev, N.D. Ouart *et al*, Proceedings of the Japan-US Workshop on Plasma Polarization Spectroscopy and the Fourth International Symposium on Plasma Polarization Spectroscopy, edited by Takashi Fujimoto and Peter Beiersdorfer, NIFS-Proc-**57**, 46-56 (2004)

Time resolved UV spectroscopy on the Alcator C-MOD tokamak

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A flat field grating spectrometer has been installed on Massachusetts Institute of Technology's Alcator C-MOD tokamak. This spectrometer is being used to measure and monitor the presence of impurity ions. The spectrometer employs a variable space grating with a spacing of 2400 lines/mm that covers the 10-70 Å wavelength band. The spectrometer has a time resolution of about 5 ms. Here we present results of the Alcator C-MOD experiments conducted during spring of 2010. The typical spectra contain lines from such elements as boron, argon, calcium, fluorine, and tungsten. We will also discuss how this work can be integrated into a high school classroom as a means to educate students about energy research as well as atomic and plasma physics. This will also equip students with the understanding and skills of how science and research are accomplished in a professional setting.

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Time resolved spectroscopy in the thin non-LTE plasma of a fluorescent tube

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The fluorescent tube provides a good opportunity to investigate properties of thin, non-LTE plasmas. Even though this type of discharge lamp has been around since the 1930s all aspects of the physics inside the lamp are not yet fully understood. This is especially true for the cathode region, where the plasma deviates the most from LTE. At Lund Observatory a project with the intention of investigating the cathode region has been started. Here, a microprocessor synthesizes the driving voltage of the tube and simultaneously sends gate pulses to the image intensifier in a CCD detector mounted on a Czerny-Turner spectrometer. In this way the intensity of different spectral lines as a function of time can be measured, giving valuable information about the different excitation mechanisms which takes place inside the plasma.

Study of a strongly dispersive solitary wave in two-component plasma

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The present paper will explore the nonlinear Schrödinger equation (NLSE) to illustrate one-dimensional propagation of a dispersive strongly wave. Using the cold ion model and the Boltzmann distribution for the electron, the NLSE can be reduced to a two-dimensional equation of motion in the presence of a cylindrically symmetric Sagdeev potential [1]. The solitary waves are studied using Sagdeev pseudo-potential technique. The solitons can have positive or negative potential depending on the fractional group dispersion coefficient relative to nonlinearity coefficient.

[1] K. Nishikawa and M. Wakatani, *Plasma Physics*, 3rd edition, Springer (2000).

New and Revised Assignments of Solar Fe XI, Fe XII, and Fe XIII Lines in the Extreme Ultraviolet Wavelength Range near 200 Å

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A detailed investigation of the iron emission lines in the 170–210 Å region revealed a discrepancy between the line list implemented in the CHIANTI code and the that available from NIST [1]. The lines at issue were from Fe XI, XII, and XIII. This wavelength region is covered by the low-wavelength channel of the Extreme Ultraviolet Imager (EIS) on board the *Hinode* satellite. We resolved this discrepancy by conducting detailed laboratory studies in which differing amounts of the relevant ions were produced and the line emission from each ionization state was recorded. Our measurements reveal five lines in Fe XI, XII, and XIII between 200 and 205 Å that do not agree with the wavelength assignments in the current database given by the National Institute of Standards and Technology; our measurements instead confirm the assignments used in CHIANTI.

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[1] *Measurement and Modeling of Density-Sensitive Lines of Fe XIII in the Extreme Ultraviolet*, N. Yamamoto, T. Kato, H. Funaba, K. Sato, N. Tamura, P. Beiersdorfer, J. K. Lepson, Astrophysical Journal **689**, 646 (2008).

A Brief Overview of the Fusion and Astrophysics Data and Diagnostic Calibration Facility

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The *F*usion and *Ast*rophysics (FAST) Data and Diagnostic Calibration Facility located at the Lawrence Livermore National Laboratory is a state-of-the-art facility used to calibrate radiation based diagnostics and study atomic processes for investigating fusion and astrophysical plasmas. FAST has at its disposal a full suite of radiation generation and detection devices, including two electron beam ion traps: EBIT-I and SuperEBIT and an absolutely calibrated x-ray calorimeter spectrometer. FAST covers the energy range between 0.01 and 100 keV, and can thus be used to calibrate a variety of plasma diagnostics. Instrument parameters that can be calibrated include line profiles, transmission and reflection efficiencies, and the quantum efficiency of grating and crystal spectrometers and solid-state detectors. FAST can be used to test fully integrated instrumentation, and is ideal for spectrometers and detectors to be flown on orbiting observatories, sounding rockets, used as ground support equipment to verify flight instrumentation, in laboratory astrophysics experiments, and to diagnose magnetic and inertial confinement fusion plasmas. Here we present an overview of the calibration capabilities of this facility including some results.

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Hyperfine quenching of the metastable $4s4p\ ^3P_{0,2}$ of Zn-like ions

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The hyperfine-quenched $4s4p\ ^3P_{0,2}$ - $4s^2\ ^1S_0$ transition rates for Zn-like ions are calculated using a large-scale relativistic configuration interaction method for 24 isotopes with Z = 30 - 66. Coherent hyperfine-mixing effects between the $4s4p\ ^{1,3}P_1$ states are included in a perturbative as well as a radiation damping approach. We find that it is important to include adequate electron correlations to yield reliable quenching rates especially in low-Z region, and that contributions from the $^1P_1$ state are substantial and must be included coherently with those from the $^3P_1$ state. For the $^3P_2$ state, hyperfine-quenched decays to the ground state yield differential lifetimes for the hyperfine states. Furthermore, additional contributions from the E2 hyperfine interaction, though usually small at less than 5%, can be as large as a factor of 3 for the ^{161}Dy and ^{163}Dy isotopes.

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Using Laboratory Measurements of Silicon along with Theoretical Calculations to identify Features in the Extreme Ultraviolet Spectra of the Sun and other Cool Stars

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Spectral models relying on theoretical atomic data from older spectral models (for eg. MEKAL, Mewe, Kaastra and Liedahl 1995) often cannot reproduce the wealth of lines observed in the astrophysical sources suggesting that the databases are either incomplete or the wavelengths are inaccurate, or both. The weak blended lines from astrophysically abundant ions like ions like Silicon, Magnesium and Sulphur can form a quasi-continuum that elevates the background mimicking a hot Bremsstrahlung background radiation.

We present the measurements of Silicon (Si V- Si XII) taken on the Lawrence Livermore electron beam ion trap EBIT-II in the wavelength range 30-120 Å along with synthetic spectra calculated using the Flexible Atomic Code (FAC) to identify previously unidentified Silicon features in the Solar spectra (Hinteregger et al, 1981 -often used as a Solar reference spectrum) and in the X-ray spectra of Procyon, a nearby F-type star which has been observed using the Low Resolution Grating Spectrometers (LETGS) aboard Chandra X-ray Observatory. This is part of a comprehensive effort to produce a catalog of emission lines in the extreme ultraviolet and benchmark the existing atomic databases.

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New identifications of Fe XIV-XVI in the solar EUV spectrum

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In the 1970's and early 1980's sounding rockets catalogued the Sun's Soft X-ray and Extreme Ultra-Violet spectrum. Today a large amount of these solar lines are still unidentified. Additionally, many of the lines that have been identified have never been verified. Through the use of the Electron Beam Ion Trap at Lawrence Livermore National Laboratory and Flexible Atomic Code calculations we have modeled the Soft X-ray and EUV spectrum of FeXIV-XVI in the 50-150 Å band. Through these models we propose new FeXIV- FeXVI line identifications to previously unknown solar spectrum lines and verify previously identified ones. This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344.

K_α transition probabilities for Platinum and Uranium Ions

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Abstract: Platinum and uranium compounds are common in biomedical applications. These ions can absorb or emit high energy X-rays, especially through the 1s-2p, that is, K_α transitions, and can be used as the source for radiation or electron production in biomedical treatments. This report will present oscillator strengths (f), line strengths (S) and radiative decay rates (A) for the 1s-2p transitions for the nine ionic states, from hydrogen to florine like, of these two elements. The 2p subshell is filled beyond flourine. For platinum ions, K_α transitions are found to be in hard X-ray region of 64-71 keV (0.18 - 0.17 $\mathring{A}$) and for uranium ions, they in the region of 94-105 keV (0.12-0.13 $\mathring{A}$). Since the number of electrons in each ionic state is different, the number of K_α transitions is also different. Hence while there are two 1s-2p transtions (1s $^2S_{1/2}$- 2p $^2P^o_{1/2}$ and 1s $^2S_{1/2}$-2p $^2P^o_{3/2}$) for the hydrogen-like ion, there are thirty five 1s-2p transitions for the for carbon-like ion. These include both types of allowed transitions, same spin and intercombination (different spins). The transitions, especially the same-spins ones, are in general strong, the radiative decay rates are of the order of $A \sim 10^{16}/s$. However, there are also weak transitions. I will explain importance of these transitions in relevance to enhanced electron production for medical treatments[1].

The transition parameters have been obtained from configuration interaction atomic structure calculations using code SUPERSTRUCTURE[2] which includes relativistic effects in Breit-Pauli approximation.

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References:

1. A.K. Pradhan, S.N. Nahar, M. Montenegro, Y. Yu, H.L. Hang, C. Sur, M. Mrozik, R. Pitzer, J. Phys. Chem. A 113, 1235612363 (2009)
2. W. Eissner, M. Jones, H. Nussbaumer, Comput. Phys. Commun. 8, 270 (1974)

Large-scale multiconfiguration Dirac-Fock calculations on E1, M1, E2, and M2 transition rates of Si-like Fe ion

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Forbidden lines have been observed in the spectra of planetary nebulae, the solar corona, new stars, astrophysical and laboratory plasma. Some forbidden transition lines are of significant importance in applications such as plasma diagnostics and spectral analysis. The emission lines of Si-like Fe have already been observed in the solar spectrum [1] and in the solar flare spectrum [2], and there has been much work on the level structure and the E1 transition rates. Recently we did large-scale calculations on the E1, M1, M2, and E2 transition rates between the levels of the excited configurations $3s3p^3$, $3s^23p3d$ and the ground configuration $3s^23p^2$ using the GRASP2K package [3]. Electron correlation effects were taken into account systematically through the active space method. The active set is expanded to n=6, $\ell = 4$. Comparing with the previous calculations, the core valence correlation was considered in this work. It was found that the core valence correlation is important for some of transitions. For example, the influence of the core valence correlation is about 5% for the E1 transition probabilities from $3s3p^3$ to the $3s^23p^2$ ground configuration, and about 10% for the $^3F_4 - {}^3F_3$ M1 and $^3F_4 - {}^3P_2$ E2 transitions in the $3s^23p3d$ configuration.

References

[1] Behring W E, Cohen L, Feldman U and Doschek G A 1976 *Astrophys.J.* **203** 521.

[2] Dere K P 1978 *Astrophys.J.* **221** 1062.

[3] Jönsson P, He X, Froese Fischer C and Grant I P 2007 *Comput. Phys. Commun.* **177** 597.

New identifications of Fe XI-XIII in the solar EUV spectrum

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The EUV and soft x-ray spectrum of the Sun is surprisingly poorly known. Because our nearest star overwhelms the sensitive detectors on *Chandra* and *XMM-Newton*, and because *Hinode* does not gather information below 190 Å, there is much less data for the Sun than for such well studied targets as Procyon. Surprisingly, the best solar data in this wavelength band are still the observations taken on sounding rockets in the 1970s [1], [2], and which form the basis for the NRLEUV database. We present new laboratory measurements of iron, Fe XI - Fe XIII, taken with the Livermore electron beam ion trap, in the EUV region 50 - 100 Å, and use these data to identify previously unassigned lines of Fe XI - XIII in the solar spectrum.

[1] H. E. Hinteregger, J. Atm. Terr Phys., 38, 791 (1976)
[2] H. E. Hinteregger, Adv. Sp. Res., 1, 39 (1981)

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Line identification in the 2006 outburst of the recurrent nova RS Oph – Cl and Ar L-shell wavelengths

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We seek to identify features in the 24-30 \AA range of the X-ray spectrum of the recurrent nova RS Oph observed on day 26 of the 2006 outburst. We tentatively identify the features as L-shell lines from Li-like - B-like Ar and Cl. In order to confirm our identifications, we used a high resolution grating spectrometer at the LLNL Electron Beam Ion Trap to measure rest wavelengths for the strongest lines of these species. We discuss the implications of our findings for our understanding of RS Oph.

Oscillator strength of Li-like ions

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The weighted oscillator strengths and radiative decay rates are presented for $1s2s3p - 1s^2 2s$ transitions in some selected Li-like ions. The present results are obtained from multi configuration Dirac-Fock wavefunctions with the inclusion of higher order relativistic corrections [1-2]. The level crossing and the effect of Breit interaction on the transition rates are analyzed .The radiative rates have been compared with those from other approaches [3-5]

References

[1] C.Froesce Fischer, T,Brage, and P.Jonnson, *Computational Atomic Structure* IOP, Bristol (1997).

[2] P.Jonsson, X.He ,C.F.Fischer, *The graspVU package*, Tech.Report DOE/ER/US, Department. of Energy (1998).

[3] Chen M.H *etal*., Atm. Data and Nucl. Data Tables, **34**,301 (1986).

[4] Goryayev and Vainshtein L.A. arXiv:physics/0603164v2 3April 2006

[5] Joseph Nilsen, Atm.Data.Nucl.Data.Tables. **38** , 339 (1988).

New analysis of the spectrum of xenon eight times ionized, XeIX

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The spectrum of Xe IX belongs to the isoelectronic sequence of Pd. These ions have a closed $4d^{10}$ shell in the ground state and offer the possibilities for a laser effect in the EUV spectral region [1, 2].

In the present work, new energy levels belonging to the $4d^9$4f, 5f and 6p configurations and new transitions are reported.

To obtain the spectrum a capillary-pulsed discharge built at the CIOp to study ionized noble gases was used [3].

Theoretical calculations using HFR, Cowan and GRASP codes for determining oscillator strengths, transition probabilities and lifetimes of the levels involved in the studied transitions were made. In the HFR calculation the even configurations $4d^{10}$, $4d^9$ns (n=5, 6), $4d^9$nd (n=5, 6), $4d^8$5s^2, $4d^8$5s5d, $4p^5$4d^{10}5p, $4p^5$4d^{10}4f and the odd configurations $4d^9$np (n=5, 7), $4d^9$nf (n=4, 6), $4d^8$5s5p, $4d^8$5snf (n= 4, 5), $4p^5$4d^{10}5s, $4p^5$4d^{10}5d were included. The electrostatic parameters were optimized by a least-square procedure to improve the adjustment to experimental energy levels

[1] S.S. Churilov, A.N. Ryabtsev, W.-Ü.L. Tchang- Brillet and J-F Wyart, Phys. Scr. 66, 293-307 (2002)
[2] B.E. Lemoff, G.Y. Yin, C.L Gordon III, C.P.J. Barty and S.E Harris, J. Opt. Soc. Am B 13, 180-184 (1996)
[3] J. Reyna Almandos, F. Bredice, M. Raineri and M. Gallardo, Phys. Scr. T134 014018 6pp (2009)

The TITAN facility at TRIUMF: Investigating rare isotopes using ion traps

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The research program at TRIUMF's ion trap for atomic and nuclear science (TITAN) is dedicated to precision experiments [1], among those mass measurements play a key role. This is done by injecting the continuous radioactive ion beam, supplied by the ISAC on-line facility at TRIUMF, into a radio-frequency quadrupole for cooling and bunching. The TITAN setup is uniquely equipped with an electron beam ion trap (EBIT) [2], which enables to increase the charge state of the ions before injection into the Penning trap. This is boosting the precision of the mass measurement by a factor proportional to the reached charge state.

EBITs are a well established tool for spectroscopy on stable ions in arbitrary charge states [3]. Measurements of isotopic shifts are examples for the confluence of atomic an nuclear physics. Beyond the precision boost by charge breeding the TITAN-EBIT at TRIUMF offers unique opportunities for the investigation of long isotopic and isobaric chains and hence effects of the nuclear size, mass, and charge radius.

This poster will present an overview of the TITAN facility and the ongoing research. Upcoming measurements shall be addressed.

[1] J. Dilling et al, *Int. J. Mass Spec.* **251** (2006).
[2] G. Sikler et al, *Europan Physical Journal A*, **25** (2005).
[3] P. Beiersdorfer*, Canadian Journal of Physics*, **86** (2008).

The $3s^2 3p3d\ {}^3F^o$ term in the Si-like spectrum Fe XIII

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In Si-like ions such as Fe^{12+} (spectrum Fe XIII), the level ranges of the lowest excited configurations, $3s3p^3$ and $3s^2 3p3d$, overlap. The lowest term of the latter configuration is ${}^3F^o$ with three fine structure levels of very different lifetimes (from nanoseconds to milliseconds). These levels eluded early observations so that analyses based on least-squares optimization of the level structure could only estimate the level positions [1]. The J=2 level decay was eventually recognized in delayed beam-foil spectra and the J=3 level decay identified in solar spectra [2]. The longest-lived level, J=4, was noted in a heavy-ion storage ring experiment as a cascade feeding the $3s^2 3p^2\ {}^1D_2$ level of the ground configuration [3]. However, since the J=4 level has several decay branches, each of them is relatively weak, and none of them has ever been reported from observation.

The game has changed with the introduction of Multireference Møller-Plesset calculations. Vilkas and Ishikawa [4] have calculated the Fe XIII levels with high accuracy so that errors in data compilations could be spotted. Their calculations also give level energies of the $3s^2 3p3d\ {}^3F^o_J$ levels that are accurate enough to make a fresh search in experimental data worthwhile. Indeed, after minor adjustments of the level values, a fair number of lines in the EUV spectra of the solar corona (observed by instruments on Skylab, *SOHO*, and *Hinode*) have been found that consistently fit in with the newly established level structure.

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[1] É. Biémont, Phys. Scr. **33**, 324 (1986)
[2] E. Träbert, Mon. Not. R. Astron. Soc. **297**, 399 (1998)
[3] E. Träbert, G. Gwinner, A. Wolf, E. J. Knystautas, H.-P. Garnir, and X. Tordoir, J. Phys. B: At. Mol. Opt. Phys. **35**, 671 (2002)
[4] M. J. Vilkas and Y. Ishikawa, J. Phys. B: At. Mol. Opt. Phys. **37**, 1803 (2004).

Measurements and calculations of Zn-like heavy ions – an update

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Previous observations of high-*Z* Cu- and Zn-like ions of elements Yb (*Z*=70) through U (*Z*=92) in an electron beam ion trap (EBIT) (see [1,2]) differed systematically from the results of laser-produced plasma experiments [3]. However, for Cu-like ions (with a single electron in the valence shell), the agreement of EBIT observations with highly developed theory (including QED) was excellent, whereas for Zn-like ions (two valence-shell electrons) a 6000 ppm deviation between measurement and *ab initio* calculations was noted. For Ga- and Ge-like ions, the discrepancy between prediction and observation was even larger. The comparison with theory has highlighted the need for much better calculations of ions with more than one electron in the valence shell, and a number of calculations have since addressed these atomic systems. We review the progress since achieved on Zn-like ions and present new Multi-Reference Møller-Plesset calculations (with a universal Gaussian basis set [4]) as well as EBIT observations of Zn-like Pt^{48+} ions (*Z*=78) in the EUV. In this case, our latest calculations agree with experiment to within 60 ppm.

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[1] E. Träbert, P. Beiersdorfer, and H. Chen, Phys. Rev. A **70**, 032506 (2004).
[2] E. Träbert, P. Beiersdorfer, K. B. Fournier, and H. Chen, Can. J. Phys. **83**, 829 (2005).
[3] C. M. Brown, J. F. Seely, D. R. Kania, B. A. Hammel, C. A. Back, R. W. Lee, and A. Bar-Shalom. At. Data Nucl. Data Tables **58**, 203 (1994).
[4] G. L. Malli, A. B. F. Da Silva, Y. Ishikawa, Phys. Rev. A **47**, 143 (1993).

Analytical study of electrostatic ion beam traps

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The use of electrostatic ion beam traps requires to set many potentials on the electrodes [1], making the tuning much more difficult than with quadrupole traps. In order to obtain the best trapping conditions, an analytical formula giving the electrostatic potential inside the trap is required.

In this poster, we present a general method to calculate the analytical expression of the electrostatic potential in any axisymmetric set of electrodes. We use conformal mapping to simplify the geometry of the boundary. The calculation is then performed in a space of simple geometry [2]. We show that this method, providing excellent accuracy, allows to obtain the potential on the axis as an analytic function of the potentials applied to the electrodes, thus leading to fast, accurate and efficient calculations.

We apply those results to the determination of a stability map depending on the potentials. It enabled us to find the good trapping conditions for O4+ at much higher energies than what has been achieved until now.

[1] D. Zajfman, O. Heber, L. Vejby-Christensen, I. Ben-Itzhak, M. Rappaport, R. Fishman, and M. Dahan, Phys. Rev. A 55, R1577 (1997)
[2] S. Bertram, Journal of Applied Physics 13, 496 (1942).

K-Shell Spectroscopy of Au Plasma Generated with a Short Pulse Laser

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The production of x-rays from electron transitions into K-shell vacancies (K-α/β emission) is a well known process in atomic physics and has been extensively studied as a plasma diagnostic in low and mid Z materials[1-2]. Such spectra from near neutral high-Z ions are very complex and therefore difficult to describe with atomic calculations. In this experiment a high Z (gold) plasma was created with a short pulse laser producing a complex non-local thermodynamic equilibrium (NLTE) plasma. A transparent bent quartz crystal spectrometer with a hard x-ray energy window, ranging from 17 to 102 keV, was used to measure the emission spectrum. The Titan laser system at Lawrence Livermore National Laboratory was used to deliver an approximately 350 joule laser pulse, with a 10 picosecond duration and a wavelength of 1054 nm, to the Au target.

K-$\alpha_{1,2}$ and K-$\beta_{1,2,3}$ transitions were observed over a range of target sizes. Additionally, a series of shots was conducted with a pre-ionizing long pulse (3 nanosecond, 1-10 joule, 527 nanometer) on the backside of the target. FLYCHK[3], an atomic NLTE code designed to provide ionization and population distributions, will be used to diagnose the plasma temperature, density and ionization states. This information will ultimately be used to gain insight into how the plasma conditions affect the production of positrons. Comparisons will also be made between Au and Eu plasmas for similar laser conditions.

[1] Kneip, S. *et al.* HEDP **4** 41-48 (2008)
[2] Jiang, Z. *et al.* Phys. Plasmas **2** 5 1702-1711 (1995)
[3] Chung, H. *et al*. http://nlte.nist.gov/FLY/ (2008)