EUV SPECTROSCOPY OF HIGHLY CHARGED IRON IONS WITH A LOW ENERGY COMPACT EBIT

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Spectroscopic investigations of highly charged ions are very important not only for atomic physics but also for astrophysical and laboratory fusion plasmas. For example, the atomic data of highly charged iron ions with charge state around 10 are strongly needed for the spectroscopic diagnostics of the solar corona with the recently launched satellite Hinode. For spectroscopic studies of such moderately charged ions, we have recently constructed a compact electron beam ion trap (EBIT)[1]. The electron energy range of the present EBIT is 100-1500 eV, which is rather low compared to that of ordinary EBITs, and thus enabled us to downsize it. We have also developed a dedicated slitless spectrometer consisting of a 1200 lines/mm laminar-type replica diffraction grating and a back-illuminated CCD. The cross sectional view of the EBIT and the spectrometer is shown in Fig.1. It is possible to employ a slitless type of spectrometer because an EBIT represents a line source with a width of ~0.1 mm. Typical EUV spectra of highly charged iron ions are shown in Fig.2. As shown in this example, various charge state ions can be selectively produced with a narrow charge state distribution by adjusting the electron beam energy. Thus the charge state of unknown lines can be identified through such energy dependence measurements. On the other hand, the electron density dependence of line ratios, which are very important for plasma diagnostics, can be studied by changing the electron beam current at a fixed energy. First results of the new EBIT are presented.

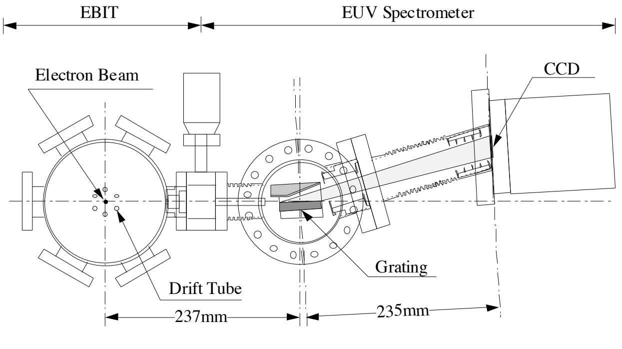

Fig.1 Cross sectional view of the EBIT and the spectrometer

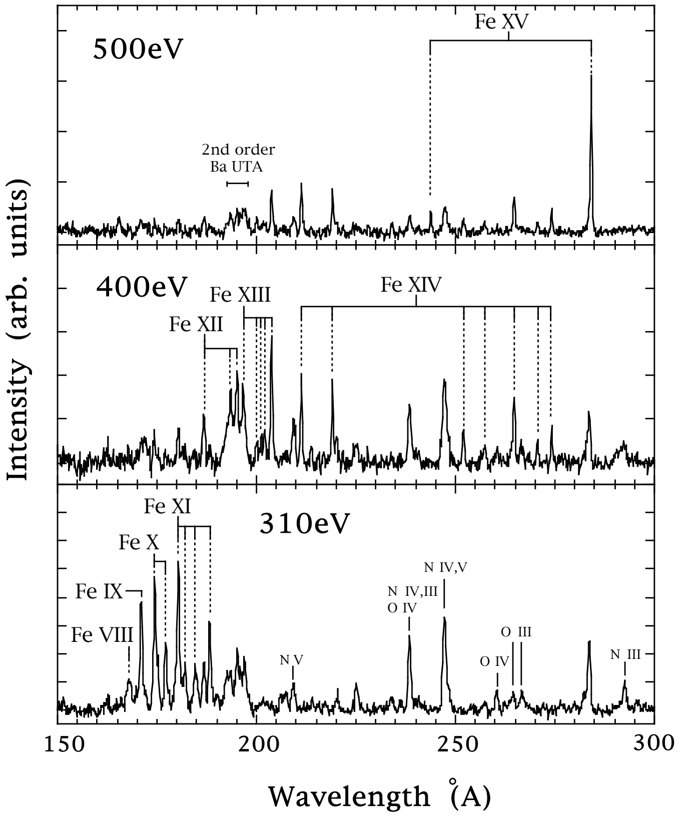

Fig.2 Typical EUV spectra of highly charged iron ions

References
[1] N. Nakanura et al., Rev. Sci. Instrum. (2008) in press.

MEASUREMENT of K_{β_2}/K_{β_1} RATIO FOR HE-LIKE KRYPTON

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In a previous measurement of intensity ratios of the $n = 3 \rightarrow 1$ intecombination line ($1s3p\ ^4P_1 \rightarrow 1s^2\ ^1S_0$, or K_{β_2}) to that of the resonance line ($1s3p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$, or K_{β_1}), it was shown that theoretical predictions underestimate the measured values for several ions with intermediate Z from magnesium to iron [1]. Among several reasons for the discrepancy, the effects of polarization of the emitted X-ray lines were mentioned as a possible cause, as the measurement was carried out on an electron beam ion trap, where the unidirectional beam creates linearly polarized light, and the X-rays were detected with crystal spectrometers, which have different reflectivities for the two polarized components. In this paper, we report the measurement of the K_{β_2}/K_{β_1} ratio of the He-like Krypton using an X-ray microcalorimeter and the electron beam ion trap SuperEBIT at Lawrence Livermore National Laboratory. The microcalorimeter is an energy dispersive device whose quantum efficiency is independent of the polarization degree of the X-ray photons. Although the linear polarization indirectly affects the measured ratio through the anisotropic factor due to the fact that the photons are detected in the direction perpendicular to the electron beam, such dependences are much weaker than those affecting the crystal spectrometers. We compare the measured K_{β_2}/K_{β_1} ratio with several theoretical predictions, and show that they underestimate the measured value, consistent with the previous results for lower Z ions from magnesium to iron.

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References

[1] A.J. Smith, P. Beiersdorfer, K.J. Reed, A.L. Osterheld, V. Decaux, K. Widmann, and M.H. Chen, Phys. Rev. A, **62**, 012704 (2000)

EBIT X-RAY MICROCALORIMETER MEASUREMENTS OF THE K-SHELL EMISSION FROM HELIUMLIKE IONS

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The K-shell emission from highly charged heliumlike ions has played an important role in EBIT spectroscopy since the first electron beam ion trap was put into operation. Early on, the spectra have been studied with high-resolution crystal spectrometers, and many of their properties have been determined during these measurements [1]. Together with the K-shell emission lines of hydrogenlike ions, the K-shell emission lines of heliumlike ions have also been used to set the wavelength scale in a variety of crystal spectrometer measurements of the transition energies of more complex spectra. Continuing the latter tradiation, we now use the K-shell emission of highly charged ions as calibration references to set the energy scale of the EBIT calorimeter spectrometer (ECS). The x-ray microcalorimeter [2] is used for measuring the complex x-ray emission from multiple shells over a broad energy range (typically 0.4 to 15 keV). Such emission may be produced, for example, by multi-electron ions from high-Z elements, such as W or Au, or by ion-atom collisions. In order to calibrate such a broad energy range, reference lines from multiple K-shell ions must be recorded.

Here we present an overview of the K-shell x-ray spectra measured with the ECS that fall into the energy regime between 400–14,000 eV. These include the more commonly studied K-shell spectra from heliumlike ions of noble gases (neon, argon, and krypton) and of the transition metals (e.g., iron, nickel). These also include the spectra of less studied heliumlike ions, inlcuding those of nitrogen, fluorine, silicon, sulfur, chlorine, and germanium.

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References

[1] P. Beiersdorfer, Can. J. Phys. **86**, 1 (2008).

[2] F. S. Porter, P. Beiersdorfer, K. Boyce, G. V. Brown, H. Chen, J. Gygax, S. M. Kahn, R. Kelley, C. A. Kilbourne and E. Magee, and D. B. Thorn, Can. J. Phys. **86**, 231 (2008).

ANALYSIS OF EUV SPECTRA FROM HIGHLY CHARGED IRON IONS WITH A COMPACT EBIT

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For the analysis of line spectra of astrophysical plasma and solar plasma, various analysis tools have been developed. However the most of the tools haven't been checked by applying the models to the laboratory plasma which can control plasma parameters. For developments of the analysis tool with high precision, selections of atomic data (wavelength (level energy), radiative transition probabilities, collisional excitation cross sections etc.) and constructions of the collisional-radiative model for spectral line analysis are important.

For these subjects, an equipment of a compact electron beam ion trap (EBIT). The compact EBIT can control electron temperature of 100 – 1500 eV and electron density around 10^{11} cm^{-3}. In this study, iron ions line spectra were measured by extreme ultraviolet (EUV) flat-field grating spectrometer (See a presentation by Sakaue et al. in this conference).

The iron ions line spectra were analyzed by constructing a new collisional-radiative model. An electron velocity distribution was taken to be a delta function for calculations of reaction rates corresponding to mono-energetic electron energy of the compact EBIT. In this paper, especially, electron density diagnostics by line intensity ratios around 10^{11} cm^{-3} were studied.

Our results in this paper are connected with applications to EIS (EUV Imaging spectrometer) observations of HINODE satellite which is solar observation satellite, and other X-ray/EUV observation satellites.

References
[1] N. Nakanura et al., Rev. Sci. Instrum. (2008), in press.
[2] N. Yamamoto et al., (2008), submitted

EUV SPECTROSCOPY OF TIN AND XENON IONS WITH A COMPACT ELECTRON BEAM ION TRAP

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Since an electron beam ion trap (EBIT) was originally developed for studying few-electron heavy ions to test fundamental quantum theories, almost all EBITs in the world have been designed to be operated with rather high electron beam energy (~10 keV or more). With such a high-energy electron beam, light and moderate elements are easily ionized to few-electron or bare ions. On the other hand, recently, spectroscopic studies of moderate charge state ions which still keep many electrons are attracting the attention of several areas. For example, to develop an EUV light source for the next-generation lithography, the atomic data of highly charged Sn and Xe ions with charge states around 10 are strongly needed [1,2]. For spectroscopic studies of such moderate charge state ions, we have recently constructed a compact EBIT [3].

In this paper, we present spectroscopic studies of highly charge Sn and Xe ions with the compact EBIT. Fig. 1 shows a typical spectrum of highly charged Xe ions. This high statistical quality spectrum has been obtained with an only 10-min exposure. This shows the high performance of the present EBIT. In the poster, the details of the new device are also presented.

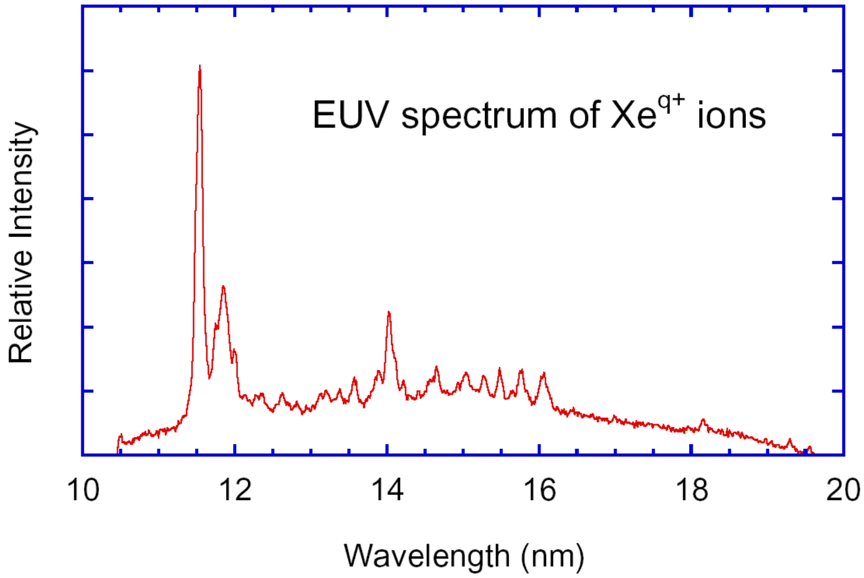

Fig.1. Typical EUV spectrum of highly charged Xe ions obtained with a recently constructed compact EBIT. The electron energy and current was 600eV and 10mA, respectively.

References

[1] G. O'Sullivan et al., AIP Conf. Proc. **771** (2005) 108.
[2] H. Ohashi et al., J. Phys.: Conf. Ser. **58** (2007) 235.
[3] N. Nakamura et al., Rev. Sci. Instrum. **79** (2008) 063104.

CHARGE STATE SELECTIVE EUV SPECTROSCOPY OF HCI AT VERY LOW COLLISION ENERGIES IN AN ELECTRON BEAM ION TRAP

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Emission spectra of HCI from xenon were recorded using the Heidelberg electron-beam ion trap (EBIT) and modelled theoretically. Transition wavelengths and probabilities were calculated using the multiconfiguration Dirac-Fock method. Electron impact excitation collision strengths were evaluated by large scale configuration interaction calculations. These predictions were used to solve the rate equations determining the population of different levels in thermal plasmas. Detailed results were given for low density plasmas at electron temperatures from 15 to 50 eV. Comparison of our theoretical model with our experimental emission spectra (see Fig. 1) obtained at beam energies as low as 40 eV proved to be a useful tool to analyze EUV emission properties of xenon plasmas. Similar experimental data for barium and iron ions were also obtained. A new high-resolution grating spectrometer has allowed further improving the quality of the data.

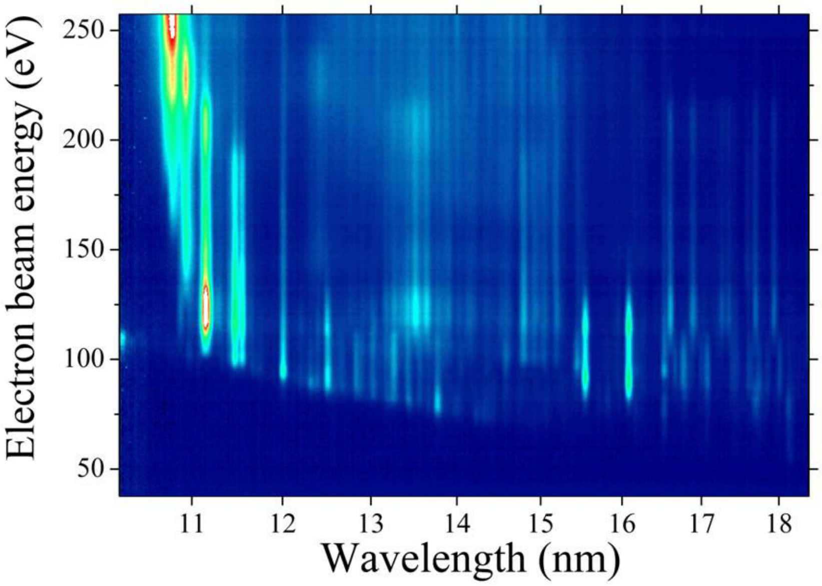

Fig. 1. Composite experimental map of the EUV emission spectra of xenon highly charged ions produced at different electron beam energies at the Heidelberg FLASH-EBIT

MEASUREMENT OF THE BOUND ELECTRON G-FACTOR IN HIGHLY CHARGED IONS BY DOUBLE RESONANCE SPECTROSCOPY

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Precise measurements of magnetic moments (g-factors) of free [1, 2] and bound electrons [3, 4] have opened possibilities to test quantum electrodynamics (QED) in free and bound systems, where strong fields are present, and to determine fundamental constants like the electron mass [5] and the fine-structure constant α [2,6]. Measurements of the electronic g_J-factor by use of the continuous Stern-Gerlach effect have been performed for the electron bound in hydrogen-like carbon $^{12}C^{5+}$ [3] and oxygen $^{16}O^{7+}$ [4]. They yield $g_J = 2.001\,041\,596\,3\,(10)(44)$ for $^{12}C^{5+}$ and $g_J = 2.000\,047\,026\,0\,(15)(44)$ for $^{16}O^{7+}$.

Here we present a double resonance technique [7] for the precise determination of the g-factor of the electron bound in heavy highly charged ions. With this technique, microwave transitions between the Zeeman sublevels of hyperfine states in hydrogen-like or lithium-like ions, which are confined in a cryogenic Penning trap, are induced. Such microwave transitions are probed by laser excitation to the upper hyperfine level and detection of optical fluorescence photons. This way, the g_F-factor of the highly charged ion is measured by laser-microwave double resonance spectroscopy. A combination of measured g_F-factors and the hyperfine transition frequency allows to simultaneously determine the electronic g-factor g_J and the nuclear g-factor g_I from one experiment, with essential input from theory. Thus, we introduce a stringent test of corresponding calculations in the framework of bound-state quantum electrodynamics in extreme electromagnetic fields and a possibility to determine nuclear magnetic moments in the absence of diamagnetic shielding.

Candidates for laser-microwave double resonance measurements are amongst others H-like and Li-like ions between lead and uranium, e.g. bismuth $^{209}Bi^{82+}$ and $^{209}Bi^{80+}$. Such experiments are planned at HITRAP, the ion trap facility for heavy highly charged ions at GSI, which is presently in the commissioning phase.

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References

[1] B. Odom, D. Hanneke, B. D'Urso and G. Gabrielse, Phys. Rev. Lett. **97,** 030801 (2006)

[2] D. Hanneke, S. Fogwell and G. Gabrielse, Phys. Rev. Lett. **100,** 120801 (2008)

[3] H. Häffner, N. Hermanspahn, H.-J. Kluge, W. Quint, S. Stahl, J. Verdu, G. Werth, Phys. Rev. Lett. **85,** 5308

[4] J. Verdu, S. Djekic, H. Häffner, H.-J. Kluge, W. Quint, S. Stahl, T. Valenzuela, M. Vogel, G. Werth, Phys. Rev. Lett. **92**, 093002 (2004)

[5] T. Beier, H. Häffner, N. Hermanspahn, S.G. Karshenboim, H.-J. Kluge, W. Quint, S. Stahl, J. Verdu, and G. Werth, Phys. Rev. Lett. **88**, 011603 (2002)

[6] V.M. Shabaev, D.A. Glazov, N.S. Oreshkina, A.V. Volotka, G. Plunien, H.-J. Kluge, and W. Quint, Phys. Rev. Lett. **96**, 253002 (2006)

[7] W. Quint, D.L. Moskovkhin, V.M. Shabaev, M. Vogel, submitted for publication

ENERGY LEVELS AND OSCILLATOR STRENGTHS FOR TRANSITIONS IN Fe XIV

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Emission lines of Fe XIV have been widely observed in a variety of solar and other astrophysical plasmas, and over a wide wavelength region varying from optical to extreme ultra-violet. The strongest observed forbidden transition is from the coronal green line ($3s^2$ 3p) $^2P^o_{1/2}$ - $^2P^o_{3/2}$ with the wavelength 5303 Å. Many of the line pairs are density and/or temperature sensitive, and hence provide useful information about physical conditions of the plasmas. However, to reliably analyse observations, atomic data are required for many parameters, including energy levels and radiative rates (A-values). Since experimental data are not available, particularly for the A-values, theoretical results are required.

Considering the importance of Fe XIV many calculations have been performed in the past, such as by Huang [1], Storey et al. [2], Safronova et al. [3], Gupta & Msezane [4], Froese-Fischer et al. [5], and Wei et al. [6]. However, most of these calculations are confined to transitions among the lowest 40 levels of the n = 3 configurations, although Gupta & Msezane and Wei et al. have also included some levels of the n = 4 configurations. Additionally, most of the available A- values are for the electric dipole (E1) transitions alone, whereas in the modelling and diagnostics of plasmas corresponding results are also required for other types of transitions, namely electric quadrupole (E2), magnetic dipole (M1), and magnetic quadrupole (M2). Therefore, the *aim* of the present work is not only to improve upon the earlier available calculations, but also to report a *complete* set of results for *all* transitions, which can be confidently applied in plasma modelling.

For our calculations we have adopted the GRASP (general-purpose relativistic atomic structure package) code, which is fully relativistic and is based on the jj coupling scheme. The n = 3 configurations generate 148 fine-structure levels. In addition, we have also included levels of the $3s3p4\ell$, $3s^24\ell$, $3s3p^55\ell$, and $3s^25\ell$ configurations. Energies for all these 332 levels and A- values among them for *all* types of transitions have been calculated. Furthermore, we have also calculated lifetimes for all levels. A complete set of all results, along with detailed comparisons, will be available during the conference.

This work has been supported by the EPSRC and STFC of the United Kingdom, and FPK is grateful to AWE Aldermaston for the award of a William Penney Fellowship.

References

[1] K. N. Huang, At. Data Nucl. Data Tables **34**, 1 (1989)
[2] P. J. Storey, H. E. Mason, P. R. Young, Astron. Astrophys. Supl. **141**, 285 (2000)
[3] U. I. Safronova, M. Sataka, J. R. Albritton, W. R. Johnson, M. S. Safronova, Phys. Rev. **A 65**, 022507 (2002)
[4] G. P. Gupta, A. Z. Msezane, At. Data Nucl. Data Tables **89**, 1 (2005)
[5] C. Froese-Fischer, G. Tachiev, At. Data Nucl. Data Tables **92**, 607 (2006)
[6] H. L. Wei, H. Zhang, C. W. Ma, J. Y. Zhang, X. L. Cheng, Phys. Scr. **77**, 035301 (2008)

ELECTRON SHAKE OFF IN THE β DECAY OF TRAPPED $^6He^+$ IONS

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In the search of physics beyond the Standard Model, nuclear β decay is a unique and relatively easy-to-access laboratory to investigate the Weak Interaction. In particular, the possible contribution of exotic couplings can be evidenced through high precision measurements of unambiguously predicted properties like the $\beta\!-\!\nu$ angular correlation parameter a. In the case of ^{6}He decay (807 ms half-life), a deviation of a from the Standard Model value -1/3 would imply the existence of tensor currents, mediated by new gauge bosons called *leptoquarks*.

Using the low energy radioactive beam line of SPIRAL in GANIL, and a transparent Paul trap as a confinement device [1], the LPC-Trap experiment has been designed to measure this $\beta\!-\!\nu$ angular correlation parameter in the $^6He^+$ beta decay with an unprecedented precision. With the radioactive $^6He^+$ ions stored nearly at rest in a small volume defined by the driving RF field of a novel transparent Paul Trap, the decay products can be detected in coincidence, and the value of the correlation parameter a can be inferred from the recoiling ion time of flight. In a recent experiment, 10^5 decay coincidences between the beta particles and the recoiling $^6Li^{2+}$ ions have been measured, yielding a relative statistical uncertainty $\Delta a/a = 2\%$ [2]. The complete analysis of the recorded data requires accounting for many factors like the background contribution, temperature of the ions in the trap, the effect of the RF field, the response functions of the detectors, and the electron shake-off effect.

Concerning this last point, the probability of shake off ionization following the beta decay process has been recently calculated for recoiling $^6Li^{2+}$ ions as a function of their recoil energy, and found to be on the order of 2% [3]. However, this effect has never been investigated experimentally for $^6He^+$ radioactive ions. We present in this work the simulations of a new setup which makes use of the existing LPC-Trap experiment to measure precisely this ionization probability.

References

[1] D. Rodriguez et al., Nucl. Instrum. Methods A 565 (2006) 876-889.
[2] X. Fléchard et al., submitted to Phys. Rev. Lett.
[3] Z. Patyk, private communication

STABILITY OF HIGHLY CHARGED FULLERENE CATIONS AND ANIONS

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The most abundant fullerenes, C_{60} and C_{70}, and all the pure-carbon fullerenes larger than C_{70} synthesized so far follow, with no exception, the isolated-pentagon rule (IPR)[1-2]. Fullerenes containing adjacent pentagons (APs) are less stable due to the additional strain. Surprisingly, recent experiments have shown that a few endohedral fullerenes[3], for which IPR structures are possible, hence expected to be the most stable ones, are stabilized in non-IPR cages. These cages are either positively or negatively charged, depending on the character of electron acceptor or electron donor of the encapsulated species. It has been argued that this unexpected stability of charged non-IPR fullerenes is associated with electronic properties of the carbon cage, such as unusually large HOMO-LUMO gaps or bond resonance energies[4,5]. These properties might be related to a reduction of strain induced by the encapsulated species, but the ultimate reasons remain unclear.

By performing density functional theory calculations[6-8] on a large number of C_{60} and C_{70} derivatives with both IPR and non-IPR cages, we show that, apart from strain, the physical property that governs the relative stability of highly charged fullerenes is the charge distribution in the cage[9]. This charge distribution is controlled by the number and location of two different structural motifs, one electrofilic (the pentalene motif, i.e., the pairs of APs,) and the other one electrophobic (the pyrene motifs). APs are the preferential sites to host additional electrons, either by adding explicitly those electrons or by making the AP bonds to react (or both). On the contrary, when one electron is removed from the fullerene cage, the resulting positive charge locates in the pyrene motifs, not in the pyrene bonds but in the more aromatic bonds surrounding the latter. Thus by playing with the number and position of pyrene bonds it is possible to generate non-IPR fullerenes with strongly non uniform positive charge distributions. We show that, when AP and pyrene motifs are uniformly distributed in the cage and well separated from each other, stabilization of non-IPR endohedral and exohedral fullerenes, as well as pure-carbon fullerene anions and cations, is more the rule than the exception. This suggests that non-IPR charged fullerenes might be even more common than IPR ones, which can be relevant to interpret recent experiments in which highly charged fullerenes are produced in collisions with ions or in storage rings.

References

[1] H. W. Kroto, Nature 1987, 329, 529-531.
[2] K. M. Kadish, R. S. Ruoff and Eds, Fullerene: Chemistry, Physics and Technology, Wiley, New York, 2002.
[3] S. F. Yang, A. A. Popov and L. Dunsch, Angewandte Chemie-International Edition 2007, 46, 1256-1259.
[4] J. Aihara, Theor. Chem. Acc. 1999, 102, 134-138.
[5] J. Aihara, Chem. Phys. Lett. 2001, 343, 465-469.
[6] S. Díaz-Tendero, M. Alcamí and F. Martín J. Chem. Phys. 2003, 119, 5545-5557.
[7] G. Sánchez, S. Díaz-Tendero, M. Alcamí and F. Martín Chem. Phys Lett. 2005, 416, 14-17.
[8] S. Díaz-Tendero, M. Alcamí and F. Martín Phys. Rev. Lett. 2005, 95, 013401.
[9] H. Zettergren, M. Alcamí and F. Martín ChemPhysChem. 2008, 861-866.

RELATIVISTIC LIGHT SHIFTS IN HIGHLY CHARGED IONS

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We investigate the level structure of heavy hydrogenlike ions in laser beams. In heavy ions, the electrons are tightly bound by the Coulomb potential of the nucleus, which prohibits ionization even by strong lasers. However, interaction with the light field leads to dynamic shifts of the electronic energy levels. We apply a fully relativistic description of the electronic states by means of the Dirac equation. Interaction with the monofrequent laser field is treated by second-order time-dependent perturbation theory. Our formalism goes beyond the Stark dipole approximation and takes into account non-dipole effects of retardation and interaction with the magnetic field components of the laser beam. This allows one to extend the theoretical description of light shifts to strong laser fields, high frequencies – e.g., x-ray lasers –, and to the highest nuclear charges. The resulting level shifts are relevant for experiments at present and near-future laser systems like the FLASH [1] and the PHELIX [2] facilities.

References

[1] S.W. Epp, J.R. Crespo López-Urrutia, G. Brenner *et al.*, Phys. Rev. Lett. **98**, 183001 (2007)

[2] P. Neumayer, R. Bock, S. Borneis *et al.*, Laser and Particle Beams **23**, 385 (2005)

Multiconfiguration Dirac–Hartree–Fock method for the calculation of static electric dipole moment in the many-electron atoms.

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A non-zero permanent static electric dipole moment (EDM) of an atom, molecule, as well as any other composite or elementary particle is one of possible manifestations of parity (P) and time reversal (T) symmetry violations. The observation of EDM of a many-electron atom may be a very important step in searching for a new physics beyond the Standard model of elementary particles [1]. One of the main possible sources of EDM in the many-electron atoms is the scalar – pseudoscalar, nuclear Schiff moment interactions between the electrons and the nucleus and permanent electron EDM. This interactions mixes parity of atomic states and also induces the EDM of an atom. In the multiconfiguration Dirac–Hartree–Fock method atomic state function (ASF) is expanded as the linear combination of configuration state functions (CSF) with same parity, total angular momentum of electrons and one of it's projection [2]. The P and T symmetry violations (induced by $S - PS$ interaction) include small admixture of other opposite parity and same total angular momentum (F) ASFs to the main ASF:

$$\widetilde{\Psi}(\gamma\nu JIFM_F) = a\Psi(\gamma\nu PJIFM_F) + \sum_{i=1}^{n} b_i \Psi(\alpha_i \nu(-P)J_i IFM_F).$$

Combining experimentally obtained limits of EDM with calculations the limit of S - PS interaction constant, nuclear Schiff momenta and electron EDM can be found. For these calculations we extended GRASP2K [3] package of the relativistic atomic structure calculations. This extension includes the programs for the interations and EDM operators matrix elements calculation.

References

[1] J.S.M. Ginges, V.V. Flambaum, Phys. Rep. **397**, 63 (2004)
[2] I. P. Grant, B. J. McKenzie, P. H. Norrington, D. F. Mayers, N. C. Pyper, Comput. Phys. Comm. **21**, 207 (1980)
[3] P. Jönsson, X. He, C. Froese Fischer,I.P. Grant, Comput. Phys. Comm. **177**, 597 (2007)

The influence of relativistic effect for the DR of many electron ion

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The influence of relativistic effect for the energy levels and dynamical process, e.g. DR process, of many electron system is the interesting objective theoretically and experimentally. The energy levels and DR cross sections of nickel-like Ta are respectively calculated by quasi-relativistic and relativistic methods. For the high-Z many electron system, the electron correlation and relativistic effects should be simultaneously treated adequately. By the comparisons of the two results, the influences of the relativistic effect for the energy levels and dynamical processes of many electron system are demonstrated in detail. This work will provide a useful criteria for the requirement of relativistic effects of many electron system.

STUDY OF INTER SUB-SHELL AND INTER SHELL ELECTRON CORRELATIONS IN $4d$ OPEN-SHELL HEAVY ATOMIC IONS

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Due to the unique structures of $N = 4$ open sub-shells in heavy atomic ions, we have a chance to observe an interesting correlation effect between $4p$, $4d$, and $4f$ orbital electrons, providing us with characteristic spectral structures of $4p - 4d$ and $4d - 4f$ optical transitions[1]. To gain an insight of this effect, which is originally pointed out by O'Sullivan and Faukner[2], we have carried out careful MCDF calculations[3] for $4d^q$ ($q = 0$ to 10) atomic ions with atomic numbers $Z = 48$ to 56. We show ,in Fig.1, the single electron atomic orbital energies for Sr-like atomic ions of $Z = 48$ to 56; we have made their MCDF optimizations including the bases up to $6p, 5d, \text{and}5f$. The differences of orbital energies between $4p$ and $4d$ orbitals, and $4d$ and $4f$ orbitals coincide within the range of a few %. The $4p^6 4d^1 4f^1$ and $4p^5 4d^3 4f^0$ configurations may mix strongly, and the optical $4p - 4d$ and $4f - 4d$ transitions may take place coherently, providing us with quite a peculiar EUV emission spectrum. We may expect that the so called the effect of spectral narrowing and shift is quite common to the atomic specieds with the atomic numbers in the range $Z = 48$ to 56.

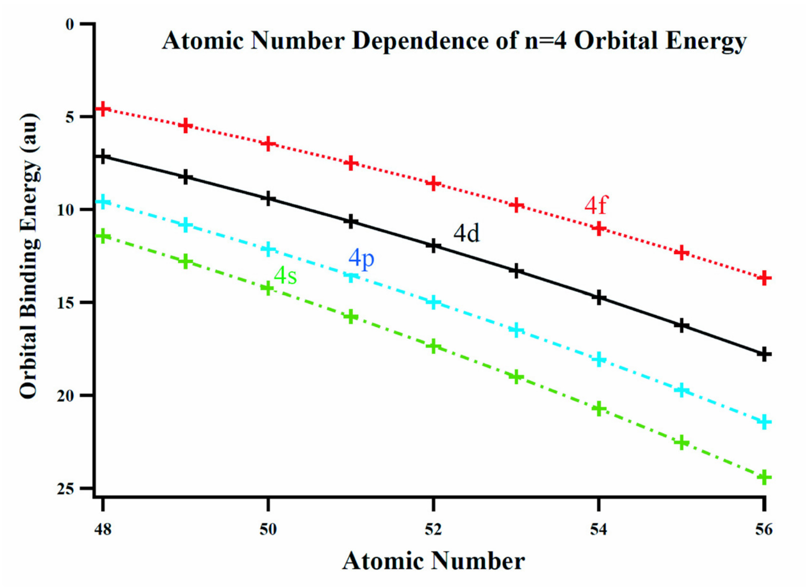

Figure 1: Atomic number Z dependence of the energies of $N = 4$ atomic orbitals. The calculated range of the atomic number is $Z = 48$ to $Z = 56$. Dotted curve: $4f$ orbital, Solid curve: $4d$ orbital, Dot-dashed curve in upper entry: $4p$ orbital, and Dot-dashed curve in lower entry: $4s$ orbital.

References

[1] G. O'Sullivan G et al 2006 *EUV Sources for Lithography Edited by V. Bakshi, SPIE Press Bellingham, Washinton, USA* 149

[2] O'Sullivan G, Faukner R 1994 *Opt. Eng.* **33**, 3978.

[3] Parpia F A, Fischer C F and Grant I P 1996 *Commpt. Phys. Commun.* **94** 249.

ACCURATE SPECTROSCOPY OF EXCITED LEVELS IN HE-LIKE URANIUM

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Electrons bound to a nucleus with a charge as high as Z=92 represent a unique probe of relativistic and Quantum Electrodynamics effects in the domain of strong fields. As compared to a one-electron and many-electron ions, heliumlike ions are the simplest multibody systems where the role electron-electron interaction in extreme conditions can be theoretically treated in a rigorous way. We present the first clear identification and highly accurate measurement of the intra-shell transition $1s2p\,^3P_2 \rightarrow 1s2s\,^3S_1$ of He-like uranium performed via X-ray spectroscopy. The present experiment has been conducted at the gas-jet target of the ESR storage ring in GSI (Darmstadt, Germany) where a Bragg spectrometer, with a bent germanium crystal, was mounted. A high systematic accuracy has been achieved making use of a differential measurement between He- and Li-like ions. With this method, it was possible to measure the $1s2p\,^3P_2 \rightarrow 1s2s\,^3S_1$ He-like U transition energy, at 4510 eV, with respect to the $1s^22p\ ^2P_{3/2} \rightarrow 1s^22s\,^2S_{1/2}$ Li-like U transition energy, at 4460 eV. First preliminary results of the data analysis will be presented.

TWO-PHOTON DECAY IN HIGHLY CHARGED HEAVY IONS: SPECTRAL SHAPE OF THE 2E1 ($2^1S_0 \rightarrow 1^1S_0$) IN HE-LIKE TIN

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The [1s2s] 2^1S_0 state of He-like ions decays to the ground state via two-photon electric dipole (2E1) transitions. The study of the spectral shape of this 2E1 decay mode in He-like ions is of interest due to its sensitivity to electron-electron correlations and relativistic effects [1]. In the present investigation, a novel experimental approach has been applied to study two-photon transitions in few-electron high-Z ions. Relativistic collisions of Li-like projectiles with low-dense gaseous matter were used to form the desired initial state [2], which allowed for a measurement of the undistorted two-photon spectral shape. The decay of the 2^1S_0 state in He-like tin was measured, following a successful earlier experiment with He-like uranium [3]. The continuum shape of the two-photon energy distribution was compared with fully relativistic calculations, which are Z-dependent. The preliminary results clearly show the best agreement with the relativistic calculations only in the region of correct nuclear charge thus confirming, for the first time, the sensitivity on Z. Detailed data analysis is still in progress.

References

[1] A. Derevianko and W.R. Johnson, Phys. Rev. A 56, 1288 (1997)
[2] Th. Stöhlker et al., Phys. Rev. A 57, 845 (1998)
[3] J. Rzadkiewicz et al., Phys. Rev. A 74, 012511 (2006)

THEORETICAL SIMULATION OF EXTREME ULTRAVIOLET SPECTRA OF TIN IN LASER-PRODUCED PLASMAS

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The emission of extreme ultraviolet (EUV) radiation from laser-produced tin plasmas is being studied extensively for its application in next generation semiconductor manufacturing technology. However, for pure Sn plasmas, the opacity is so high that 13.5 nm radiation emitted from deep within the plasma core is absorbed strongly during propagation through the surrounding plasma as it expands [1]. In addition, the spectrum of tin in the EUV range does not consist of sharp and well separated features, but a bright quasi-continuum band or unresolved transition array (UTA).

Extreme ultraviolet (EUV) emission spectra from laser-produced Sn plasmas have been experimentally investigated at different power densities in the 9.5-18 nm wavelength range. Experimental results indicate the presence of a broad reabsorption band and some pronounced dips because of opacity effects in the spectra. With increasing power densities, the reabsorption band shifts to the shorter wavelength side and the absorption dips become deeper.

Theoretical calculations using the Cowan code [2] show that the dips arise from the 4d-4f and 4p-4d transitions. Using detailed configuration accounting (DCA) with the term structures treated by the unresolved transition array (UTA) model [3], we analyze the opacity effects and simulate the spectra, as is indicated in figure 1. By comparing the results of the simulations with experiments, it can be concluded that the spectra from a pure Sn target contains both emission and absorption, with electron temperatures ranging from 28 to 15 eV, and electron densities from 5.0×10^{20} to 3.7×10^{19} cm^{-3}, in going from the core to the outer plasma region.

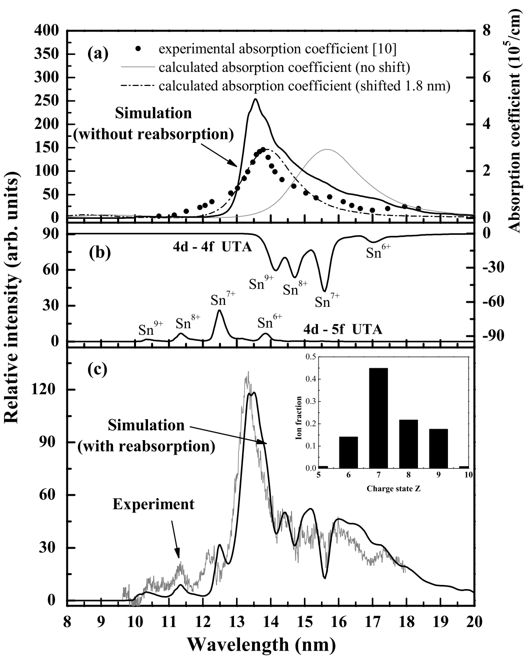

Fig. 1 Theoretical simulation and comparison of laser produced Sn spectrum.

References

[1] Y. Tao , S. S. Harilal, M. S. Tillack, K. L. Sequoia, B. O'Shay and F. Najmabadi, Optics Letters **31**, 2492 (2006).

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

[3] J. Yan and J. M. Li. Chin. Phys. Lett. **17**, 194 (2000).

Visible spectroscopy with the Tokyo-EBIT

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Visible lines from highly charged ions, which can be used for diagnostics of plasmas, have been investigated extensively theoretically and experimentally. The investigations of the M1 transitions of Ti-like ions with EBIT are one of such examples [1].

Because W has been used as the plasma facing diverter wall due to the favorable physicochemical properties of this element, highly charged W ions exist in fusion plasmas for the sputtering of the diverter material. Therefore lines in the visible region from highly charged W ions can be one of the candidates for the diagnostics of fusion plasmas. Doron and Feldman [2] investigated theoretically visible and near UV transitions within N-shell ground state configurations of W. They showed that the intensity ratios of lines originating from transitions within the $4p^64d^5$ configuration of W^{33+} and $4p^64d^7$ of W^{31+} strongly depended on the electron density of plasmas. These lines could be used for diagnostics.

We have investigated visible lines from highly charged W ions with the Tokyo-EBIT. Since Doron and Feldman predicted that some lines arising from $4p^64d^k$ ground configurations could be observed in the range from 360 to 390 nm [2], our measurements were focused on the range from 350 to 400 nm and on the electron energy range from 1.1 to 1.7 keV. Several lines arising from highly charged W ions were observed in addition to the lines from lower charge state W ions.

References

[1] H. Watanabe, D. Crosby, F. J. Currell, T. Fukami, D. Kato, S. Ohtani, J. D. Silver, and C. Yamada Phys. Rev. A **63**,042513(2001).

[2] R. Doron and U. Feldman Phys. Scr. **64**,319(2001).

QED PERTURBATION THEORY IN CALCULATING NUCLEAR QUADRUPOLE MOMENTS AND HYPERFINE STRUCTURE PARAMETERS FOR LI-LIKE MULRICHARGED IONS

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Relativistic calculation of the spectra, hyperfine structure (hfs) parameters for heavy atoms and multicharged ions with account of relativistic, correlation, nuclear, QED effects [1,2] is carried out. Method is based on the gauge-invariant QED perturbation theory and generalized dynamical nuclear model [1]. The Fermi model has been used for modelling the distribution of charge in a nucleus. The results of the test calculation of the hyperfine structure parameters for H-like ion with nuclear charge Z=170 (plus derivatives of energy contributions on nuclear radius) are presented. A contribution of the relativistic, nuclear and radiative corrections is definitive one for H-like ion with Z=170. Calculation of the hfs parameters, splitting energies, constants (plus derivatives from energy contributions, the nuclear electric and vacuum-polarization potentials on nuclear radius) for Li-like ions with Z=20-100 is carried out. It is carried out an analysis of the inter-electron correlations, nuclear, radiative effects contributions, including an analysis of the role for nuclear effects contribution (core-polarization ones, which are induced by valent protons of a nucleus), temporal distribution of magnetization in a nucleus and high order QED corrections. As example table 1 contains data on hfs parameters $A=Z^3 g_I \overline{A}$, $B=\frac{Z^3 Q}{I(2I-1)}\overline{B}$ (cm^{-1}) for some Li-like ions.

nlj/Z		20	30	41	59	69	79	92
3s	$\overline{A}$	26 –03	29 –03	32 –03	43 –03	51 –03	63 –03	90 –03
4s	$\overline{A}$	15 –03	11 –03	14 –03	16 –03	19 –03	24 –03	36 –03
$2p_{1/2}$	$\overline{A}$	25 –03	30 –03	35 –03	46 –03	56 –03	71 –03	105 –02
$3p_{1/2}$	$\overline{A}$	81 –04	91 –04	09 –03	12 –03	16 –03	20 –03	31 –03
$4p_{1/2}$	$\overline{A}$	32 –04	37 –04	43–04	58 –04	72 –04	91 –04	11 –03
$2p_{3/2}$	$\overline{A}$	50 –04	55 –04	60 –04	65 –04	67 –04	71 –04	72 –04
	$\overline{B}$	9 –05	10 –04	11 –04	12 –04	13 –04	15 –04	17 –04
$3p_{3/2}$	$\overline{A}$	13 –04	14 –04	16 –04	18 –04	19 –04	21 –04	22 –04
	$\overline{B}$	31 –05	37 –05	41 –05	48 –05	51 –05	55–05	62 –05
$4p_{3/2}$	$\overline{A}$	62 –05	70 –05	77 –05	84 –05	89 –05	92 –05	10 –04
	$\overline{B}$	10 –05	12 –05	14 –05	18 –05	20 –05	22 –05	26 –05

References

[1] A.V.Glushkov, JETP Lett. **55,**108 (1992), A.V.Glushkov, L.N.Ivanov, Phys.Lett.A. **170**, 36 (1992); A.V.Glushkov, E.P. Ivanova, J.Quant. Spectr. Rad. Tr. (US) **36**,127 (1986); E.Ivanova, L.N.Ivanov, A.V.Glushkov, A.S.Kramida, Phys.Scr. **32,** 512 (1985); A.V.Glushkov, In: Low Energy Antiproton Phys. (AIP Serie) **796**, 211 (2005) ; J.Phys.CS. **11**,199 (2005);
[2] A..Glushkov, O.Khetselius etal, Nucl. Phys.A. **734**, e21 (2004); Phys.CS. **35**, 425 (2006); A. Glushkov etal, Recent Advances in Theory of Phys. and Chem. Systems, edited J.-P.Julien, J. Maruani, D.Mayuo, S.Wilson, G.Delgado-Barrio (Springer) **15**, 301 (2006); Ibid. **15**, 285 (2006).