

# ABOVE-THRESHOLD TWO-PHOTON TRANSITIONS BETWEEN BOUND STATES OF MULTICHARGED HYDROGEN-LIKE IONS

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Recent advances in production of an intense coherent x-ray radiation, either from free electron lasers or from high-order harmonics of optical laser radiation, open the possibility of experimental measurements of elastic and inelastic (Raman-like) x-ray scattering involving inner shells in heavy atoms or multicharged ions. Major difficulty in theoretical description of such processes is the summation over intermediate states of the electron in a Coulomb continuum after absorption of above-threshold photon (which energy  $\hbar\omega$  exceeds the binding energy of an initial bound state,  $\hbar\omega > |E_0|$ ). The well-known standard Sturmian expansions for the Dirac Coulomb Green Function (CGF) cannot be used for this case, since they give convergent Sturmian series for the transition amplitude only for below-threshold photons (with  $\hbar\omega < |E_0|$ ). We show that the use of generalized Sturmian expansions for Dirac CGF (involving a free (arbitrary) parameter  $\alpha$ , cf. Ref. [1]) leads to well-convergent Sturmian series for relativistic two-photon matrix elements in the above-threshold region after proper choice of the complex parameter  $\alpha$ . For nonrelativistic problems, high efficiency of generalized Sturmian expansions for CGF of the Schrodinger equation in numerical calculations of above-threshold processes was demonstrated in Ref. [2]. As the illustration of developed techniques for treatment of relativistic two-photon above-threshold transitions, we present high-precision results for the (electric-dipole) dynamic polarizability of ground state of H-like ions with  $Z < 137$  ( $Z$  is the nuclear charge) over a wide interval of above-threshold photon energies. Our techniques may be useful also for high-precision calculations in quantum electrodynamics of bound states in a strong Coulomb field.

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# PRODUCTION OF MULTIPLY CHARGED IONS FROM THE 4d PHOTOIONIZATION OF Cs<sup>+</sup>

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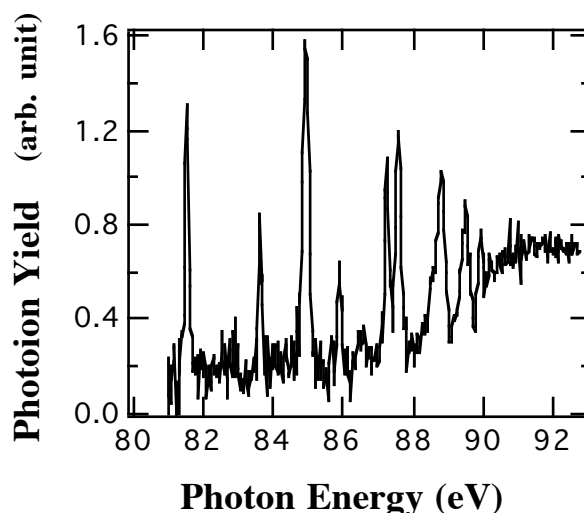
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There has been great interest in systematic studies of 4d photoabsorption of atoms with increasing ionization along with isoelectronic sequence. However, very little is known experimentally on photoabsorption for ionic species. The 4d photoabsorption spectrum of Cs<sup>+</sup> has been measured by Cummings and O'Sullivan[1] with the dual-laser-produced plasma (DLP) technique. However, because of absorption saturation the shape of the 4d giant resonance could not be deduced in their experiment. In this paper, we present the relative photoion yield spectra of Cs<sup>2+</sup> and Cs<sup>3+</sup> from a Cs<sup>+</sup> target within the 4d giant resonance region with an ion-photon merged-beam apparatus. The experimental set-up was the same as that described in Koizumi *et al* [2]. The measurements were done using the monochromatic photon beam from a high-resolution spherical grating monochromator in the BL-16B beam line at the Photon Factory for High Energy Accelerator Research Organization (KEK-PF).

Figure 1 shows the total ion spectrum below 90 eV with higher resolution ( $E/\Delta E \approx 800$ ). Some prominent discrete peaks are observed. These peaks are assigned to 4d-np,nf transitions from the theoretical study by Sato *et al*[3]. Above 90eV, a broad 4d giant resonance peak is observed clearly for Cs<sup>3+</sup> spectrum. It is worth noting that some window type resonances appear around at 100eV. Detail comparison between present data and the theoretical study will be given at the conference.



**Fig. 1.** Sum of Cs<sup>2+</sup> and Cs<sup>3+</sup> yield from Cs<sup>+</sup> target with higher energy resolution. ( $E/\Delta E \approx 800$ ).

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# X-RAY ABSORPTION BY HIGHLY CHARGED IONS IN PLASMAS: TOWARD PHOTO-PUMPING X-RAY LASER

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In the photo-pumping x-ray laser scheme, spectral line emission from particular ions is absorbed by different element ions to create the population inversion in the latter. The success of this scheme as an x-ray laser depends upon exact spectral matching between the emission line and the absorption line. The widths of the spectral lines of ions in plasma, that are due mainly to the Doppler broadening and the Stark broadening, are typically  $\sim \Delta\lambda/\lambda < 0.01\%$ . Therefore high resolution spectroscopic studies are required to find appropriate pair of the “emitter” and “absorber” ions. Indeed, in the early 1990s, the atomic physics group at the Lawrence Livermore National Laboratory (LLNL) has determined the accurate wavelengths of many spectral lines of highly charged ions by use of the electron beam ion trap (EBIT) [1, 2]. The data obtained by the EBIT group, in collaboration with the x-ray laser specialists at LLNL, was used to find the candidate pairs of ions for photo-pumping x-ray lasers.

The scheme using "emitter" ions and "absorber" ions has a technical difficulty: the emitter and the absorber ions should be located as close as possible so that the pumping emission reaches to the absorber ions efficiently. At the same time, the electron temperature should be high for the emitter to increase the emissivity of the ions, whereas the lower temperature is preferred for the absorber ions to avoid the “thermal” population in the lower lasing level, which reduces the amplification gain. This implies that the use of "emitter" and "absorber" ions in different kinds of plasmas is not practical under usual laser irradiation geometry [3].

In this presentation, we propose the use of  $K\alpha$  line from solid target as the emitter coupled with the laser-produced plasma as the absorber. We take aluminum  $K\alpha$  line (0.833816 nm) and resonance line  $2p^6-2p^54d (2p_{1/2}, 4d_{3/2})_1$  of neonlike zinc ions (0.83400 nm) as an example and calculate the excited level population of the neonlike zinc ions by use of an Monte-Carlo simulation code. The calculated result shows that substantial amplification gain in the transition of  $3p-4d$  line at a wavelength of 3.5 nm can be generated in this scheme.

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# BEHAVIOUR OF IMPURITY IONS FOR RADIATION COLLAPSE IN LARGE HELICAL DEVICE

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Impurities have an important effect on energy balance and particle transport in plasmas and play a key role for many plasma properties. This is normally the case in fusion plasmas, astrophysical plasmas and industrial plasmas. For simulation or modeling of plasmas we would like to know the absolute values of ion and electron densities, electron temperature, radiation power etc. In order to study the behavior of impurities quantitatively, spectroscopic measurements are very useful. We are studying plasma diagnostics with the use of spectroscopy. In this paper we discuss the behavior of impurities as deduced from EUV spectra measured in laboratory fusion plasmas in the LHD (Large Helical Device).

Radiation collapse in such fusion machines is related to the problems of the density limit and the threshold temperature [1]. It is also related to a balance between input power and radiation power output. Radiation collapse is thought to occur when the electron density increases, the electron temperature decreases and so the radiation loss increases significantly. However this scheme is not studied well quantitatively. Recently the effect of electric field on radiation collapse has been discussed. In order to investigate how and why plasmas collapse, we measure the impurity emission spectra.

In this paper we try to make a quantitative study of radiation collapse using spectroscopic measurement of carbon ion lines of C III, C IV and C V from LHD plasmas. We estimate the time dependent electron temperatures from the intensity ratios of spectral lines from C V and C III using a collisional-radiative model for the carbon ions. We find that the intensity ratios of C V are affected by recombination at the end of plasma. We will describe a time dependent model for carbon ions. We will also compare the radiation collapse caused by radiation from other elements such as neon, iron and xenon.

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# INVESTIGATING THE EMISSION ANGLE, CHARGE AND ENERGY OF IONS PRODUCED FROM LASER PRODUCED EXTREME ULTRAVIOLET SOURCES.

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With the ongoing miniaturisation of microprocessors in accordance with Moore's law, the physical limits of current photolithography employing deep ultraviolet radiation ( $\lambda = 193$  nm), are being reached. Laser produced plasma sources of radiation are one of the favoured candidates for the production of the 13.5 nm radiation required for Extreme Ultraviolet Lithography (EUVL) manufacture of features at the 32 nm node and beyond [1]. The choice of wavelength for EUVL is based on the availability of Mo/Si multilayer mirrors which have a 70% reflectivity at 13.5 nm [2]. Tin (Sn) and xenon (Xe) are both potential EUVL source materials as they emit strongly at the required wavelength [3,4]. Both Sn and Xe target materials emit energetic ions which can damage and greatly reduce the reflectivity of real world optics thus hindering any commercial application. It is therefore important to characterise the charge state, energy and angle of emission of ions emanating from laser produced plasmas that might be utilised in EUV lithographic applications.

The properties of ions emitted from tin based laser produced plasmas have been investigated using a spherical sector energy analyser. The analyser was used to determine the charge states and energies of ions emitted from the plasmas. The detection efficiency of the analyser has been absolutely calibrated using an Electron Cyclotron Resonance Ion Source. Angular discrimination was achieved using a custom built optical system which could be rotated in relation to the spherical sector energy analyser, whilst maintaining a normal angle of incidence for the laser pulse with respect to the target [5]. The optical system provides angular measurement, with a 1 degree accuracy, over a range from 20 – 85 degrees to the normal incident direction of the laser. The tin plasmas were generated using a Nd:YAG laser operating at 1064 nm with a full width half maximum pulse duration of 7-9 ns. Tin charge states from SnII to SnX, with energies / charge ratios spanning 0.2 – 3.2 keV, over a range of angles (20, 30, 40, 45, 50, 60, 70, and 80 degrees) were analysed.

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# Electron Temperature Modifications by Upgraded Injection Power of IBW Heating System on HT-7 Tokamak

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## Abstract:

The enhanced local and globalized electron heating has been achieved by recently upgraded ion Bernstein waves (IBWs) heating system in deuterium plasmas on HT-7 tokamak. The maximum capability of injection power of the system has been enhanced from 350 kW to 600 kW (15-30 MHz) for better and active control of current density and pressure profiles, and for discovering the new aspects of plasma heating for good particle and energy confinement. A new quadruple T-type ion Bernstein waves (IBWs) coupling antenna has also been installed, mounted in the toroidal direction on low field side in this scenario. Both on-axis and off-axis electron heating has been investigated. In the present study, the electron-heating mode was experimented by varying IBW injection power, and the investigated results are demonstrated. The enhancement in direct electron heating via electron Landau damping (ELD) from IBWs has been observed, and the bulk electron temperature showed a significant rise with a heating factor,  $\Delta(T_e \times n_e)/P_{rf}$ , up to  $9.3 \times 10^{19} \text{ eV m}^{-3} \text{ kW}^{-1}$  at central electron density ( $n_e$ )  $3.7 \times 10^{19} \text{ m}^{-3}$ . A good particle confinement has been achieved at the IBW injection power of 550 kW at frequency of 27 MHz and at toroidal magnetic field of 1.92 T. The enhancement and modifications observed in electron temperature and other plasma profiles are discussed under various plasma conditions at higher IBW injection powers. Improvement in energy confinement has also been observed in this regime.

Keywords: IBW heating; electron cyclotron emission; electron temperature.

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# OPTIMAL PULSE DURATION IN LASER-CLUSTER INTERACTIONS

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The study of the interaction of intense short laser pulses with clusters has received much attention during the last decade [1]. The ions and quasi-free electrons in the cluster form a "nano-plasma" of solid density, where the electrons are efficiently heated by the combined fields of the laser and the surrounding particles [2,3]. Electron-impact ionization produces highly charged ions as well as inner-shell vacancies, which are at the origin of X-ray radiation. As a fraction of the electrons leaves the cluster, a net positive charge is left behind and the cluster begins to expand before disintegrating completely in a Coulomb explosion.

The size of the system and the multitude of mechanisms at play provide a challenge for the theoretical description of the interaction. Due to the large number of atoms ( $N > 10000$ ) in a cluster, a full ab-initio simulation still seems impractical. We therefore opt for an open effective mean-field approach, in which many-particle effects are included via stochastic processes. The roles played by different effects such as cluster polarization, surface disintegration, and microscopic atomic dynamics (elastic electron-ion scattering, electron-impact ionization etc.) can thus be studied.

The measurement of the 3.1 keV characteristic K-shell X-ray radiation emitted from argon clusters [4] provides an excellent experimental tool to gain insight into the dynamics of the interaction on the short time-scale of the irradiating laser pulse ( $\tau > 60$  fs). High resolution X-ray spectroscopy gives access to the charge state distribution of the highly charged cluster ions  $Ar^{q+}$  with  $q > 12$ . We achieve good quantitative agreement between the simulated and experimental absolute X-ray yields, and the ionic charge-state distributions are also well reproduced at high laser intensities.

By varying the pulse duration, additional information on the interplay between ionic and electronic dynamics during the cluster explosion process can be gained. One highlight is the existence of an optimum pulse duration that maximizes the X-ray yield at constant laser pulse energy. We give an interpretation of this effect different from the previously invoked nanoplasma resonance [5].

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# On the solution of the time dependent Dirac equation for hydrogen-like systems

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The time dependent Dirac equation for a hydrogen-like system exposed intense electromagnetic radiation is solved numerically by expanding the wave function in eigenstates of the Hamiltonian. These eigenstates are obtained by diagonalizing the Dirac Hamiltonian on an exponential grid. As the field parameters (field strength and frequency) increases, both magnetic and relativistic effects become important. Furthermore, for higher nuclear charges, relativistic effects are important even for relatively weak fields. The need for a non-dipole and relativistic treatments is investigated by direct comparison with the corresponding predictions of the Schrödinger equation in the dipole approximation.

Even for fields far below the threshold for pair-creation, negative energy states may still play a role during the interaction. The possible influence of such states is studied by propagating the wave function in field dressed states, which are obtained by diagonalizing the full Hamiltonian. In order to minimize the number of basis states needed, complex scaling has been applied. This scaling also facilitates the calculation of ionization rates.

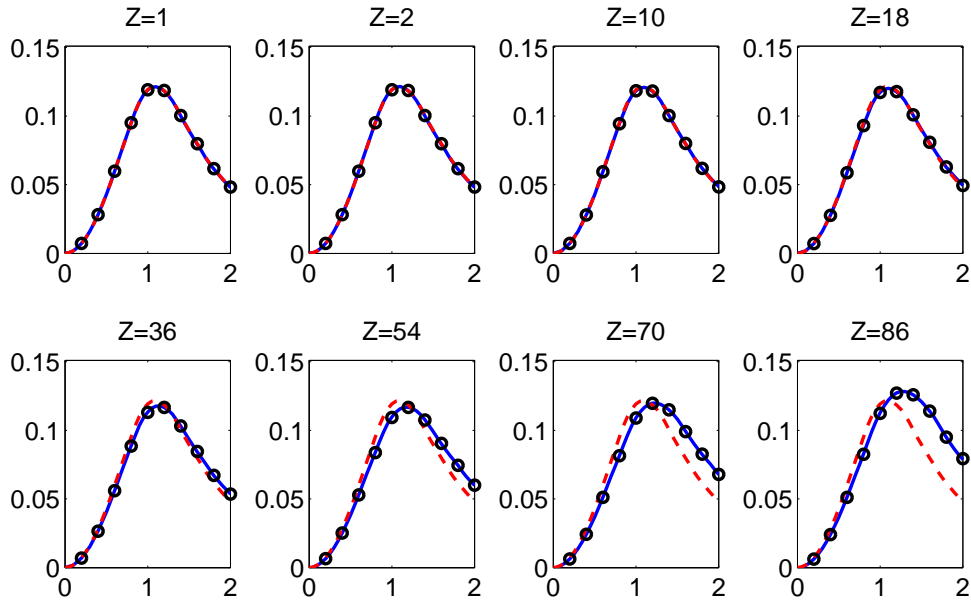


Figure 1: Ionization rates for hydrogen-like systems of different nuclear charges  $Z$  exposed to monochromatic laser light of frequency  $\omega = 1.0 Z^2$  a.u.. The electric field strength  $E_0$ , given in atomic units, is scaled with  $Z^3$ . The blue, full curve corresponds to the Dirac equation in the dipole approximation, the circles are obtained without the dipole approximation, and the red, dashed curves, which are the same for all  $Z$ , stem from the Schrödinger equation in the dipole approximation.

# QED THEORY OF LASER-ATOM AND LASER-NUCLEUS INTERACTION AND MULTI-BODY DYNAMICS IN A STRONG LASER FIELD PULSE

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QED theory is developed for studying interaction of atoms and nuclei with an intense and superintense laser field. Method bases on a description of system in the field by the  $k$ - photon emission and absorption lines. The lines are described by their QED moments of different orders, which are calculated within Gell-Mann & Low adiabatic formalism [1]. The analogous S-matrix approach is developed for consistent description of the laser-nucleus interaction. We have studied the cases of single-, multi-mode, coherent, stochastic laser pulse shape. An account for stochastic fluctuations in a field effect is of a great importance. Results of the calculation for the multi-photon resonance and ionization profile in Na,Cs, Yb, Gd atoms are presented. It is also studied the phenomenon of the above threshold ionization. Efficiency of method is demonstrated by QED perturbation theory calculations for the two-photon ionization cross-sections for extended photon energy range (including above-threshold ionization) in Mg. Comparison with the R-matrix calculation of Luc-Koenig et al is given. There is considered a phenomenon of the Rydberg stabilization of the H atom in a strong laser field and estimated the rate of transition between the stabilized Rydberg state ( $n=40, m=2$ ;  $E \sim 10(8)V/cm$ ) and ground state, when it's possible the radiation of photons with very high energy (short-wave laser amplification). DC strong filed Stark effect for atoms, including atoms in plasma, Rydberg atoms and confined systems is studied within new quantum approach, based on the operator PT [1]. The zeroth order Hamiltonian, possessing only stationary states, is determined only by its spectrum without specifying its explicit form. We present here the calculation results of the Stark resonances energies and widths for a number of atoms (H, Li, Tm,U etc.) and for a whole number of low-lying and also Rydberg states. We discovered and analyzed the weak field effect of drastic broadening of widths of the Letokhov-Ivanov re-orientation decay autoionization resonances in Tm etc. Developed approach can be naturally applied to studying the Stark effect in confined systems, including quantum wells, quantum dots etc, where especially interesting effects may occur. Modelling nuclear ensembles in a super strong laser field provides opening the field of nuclear quantum optics and is carried out in our work too. The direct interaction of super intense laser fields in the optical frequency domain with nuclei is studied and the AC Stark effect for nuclei is described within the operator perturbation theory and the relativistic mean-field (RMF) model for the ground-state calculation of the nucleus [2]. We find that AC-Stark shifts of the same order as in typical quantum optical systems relative to the respective transition frequencies are feasible with state-of-the-art or near-future laser field intensities.

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