EUV SPECTROSCOPY OF HEAVY ELEMENTS NEAR Z=74 AT THE NIST EBIT

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We report recent measurements and identifications of extreme ultraviolet (EUV) spectra for highly-charged ions of heavy elements obtained with the NIST Electron Beam Ion Trap (EBIT) [1-4]. Particular emphasis is given to ions of tungsten relevant to magnetic fusion research.

Electron beam energies varied from 2 to 20 keV, allowing us to produce ions in the range of 35+ to 68+. Detailed identification of spectral lines from M- and N-shell ions was based on large scale collisional-radiative modeling of the EBIT plasma.

We present more than 100 newly identified allowed and forbidden lines that can be used for the diagnostics of hot plasmas.

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EXPERIMENTAL STUDIES OF 3.1-3.5 KEV X-RAY SPECTRA OF HIGHLY CHARGED AU IONS AT SHANGHAI EBIT

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Spectroscopic study of highly charged Au are very important, both for atomic structure study and for hot plasma diagnostics, especially for laser induced fusion plasma studies [1-2].
In this paper, studies of M-shell X-ray spectra of highly charged Au ions were reported. The experiments were done at the newly developed electron beam ion trap at Fudan University in Shanghai, Shanghai EBIT [3]. This EBIT was designed for high electron energy operation, with electron beam energy of 2-200 keV. At present, the beam energy can cover a range of 0.9-130 keV, but with obviously much lower current at low energy, i.e. 5 mA at 0.9 keV. In the experiments reported in this paper, spectra were taken at several electron beam energies in the range of 5-20 keV, with electron beam currents of 20 to 80 mA. Low charge gold ions were produced by a home made metal vapour vacuum arc, MEVVA ion source and injected into the Shanghai EBIT during the experiments. The X-rays of highly charged Au ions in the range of 3.1-3.5 keV were dispersed by a home made flat crystal spectrometer, and recorded by a charge coupled device (CCD) detector. The crystals used in the experiments are LiF(200) (2d=0.4027nm) and SiO_2(1010) (2d=0.8512nm), with spectral resolution, $\lambda/\Delta\lambda$ around 3000.
The experimental results will be displayed and discussed in the paper.

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EXPERIMENTAL STUDY OF X-RAY TRANSITION IN LI-LIKE IONS WITH EBIT

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As mentioned in many papers[1, 2, 3, 4, 5, 6], measurements of Li-like systems can provide data to be more sensitive to higher-order QED terms than those of H-like systems, though the calculation of QED terms for Li-like ions is more complex than for H-like ions due to the presence of two additional electrons. And the treatment of QED in many-particle environment is still a field in development.

The X-ray transition in Li-like Cu^{27+} and Pb^{79+} were investigated by using flat crystal spectrometer.

The lines from Cu^{27+} were observed at Shanghai EBIT [7]. The Tokyo-EBIT [8] was used to produce and trap Li-like Pb^{79+}.

As a result, the wavelength of the $1s^2 2p_{3/2} - 1s^2 2s_{1/2}$ transition in $^{208}Pb^{79+}$ has been determined to be 2642.18±0.06 eV. In order to get the QED contribution, the Non-QED part 2667.22eV was subtracted from the measured energy. Therefore, -25.04±0.06 eV was obtained for QED contribution.

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Soft X-ray Laser Spectroscopy of HCIs with Free Electron Lasers

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Resonant laser spectroscopy of soft x-ray transitions in highly charged ions (HCIs) by means of Free Electron Lasers (FELs) has been proven [1] to be a promising technique with the potential to achieve unprecedented precision on energetic transitions unreachable by traditional laser spectroscopy. The technique relies on combining two advanced technologies, a state-of-the-art EBIT [2] with the Free electron LASer at Hamburg (FLASH [3]), measuring the resonant fluorescence yield by the trapped HCIs as a function of the wavelength of the FLASH-light.

Here we report on our latest results applying improved alignment techniques to quickly find and guarantee optimum overlap of the ion cloud and the FLASH beam. Three fundamental transitions at energies E_0 were investigated, namely $1s^22s\ ^2S_{1/2}$–$1s^22p\ ^2P_{1/2}$ in Li-like Fe^{23+} at 48.6 eV, Li-like Cu^{27+} at 55.2 eV, and $1s^22s\ ^2S_{1/2}$–$1s^22p\ ^2P_{3/2}$ in Fe^{23+} at 65.3 eV. The later demonstrates resonant laser spectroscopy of multiply or highly charged ions at more than one order of magnitude higher transition energies as reported elsewhere [4]. The resolutions achieved were around $E_0/\mathrm{FWHM} = 3000$ for the individual spectral lines, resulting in relative precisions (preliminary) of 2 parts-per-million (ppm) for determining the center-of-mass wavelength.

By means of known absorption lines present in neutral neon we were able to achieve an absolute accuracy (preliminary) in the Fe^{23+} case of roughly 20 ppm, which is close to the accuracy of the most accurate reported measurements [5]. Pushing the absolute accuracy further down (e.g. to the achieved relative precision) can hardly be done by comparison to absorption lines of rare gases, but instead requires lines of H-like and He-like low-Z ions (C,N,O,F) for calibration, which then would establish independent wavelength standards in this spectral region with ppm accuracy.

Thus, we expect significant impact of our technique on precision spectroscopy of transitions important for atomic structure theory, e.g. strong-field QED [6], or of astrophysical relevance.

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PRECISION LIFETIME DETERMINATIONS OF THE GREEN AND RED IRON CORONAL LINES IN AN ELECTRON BEAM ION TRAP

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The lifetimes of the forbidden lines of Fe XIV and Fe X (the green and red coronal lines) have been measured at the Heidelberg electron beam ion trap by monitoring its optical decay to the ground state by magnetic dipole (M1) transitions at λ= 530.29 nm and 637.64 nm, respectively. A new trapping scheme was applied to enhance sensitivity. Possible systematic effects were investigated by studying in detail the dependence of the decay curves on various trapping conditions with high statistical significance. The highly accurate result of the FeXIV [1] measurements shows an unexplained discrepancy in comparison with the average value of existing theoretical predictions. The inclusion of the electron anomalous magnetic moment within the theoretical calculations increases this disagreement, thus pointing at other possible origins of this discrepancy. The FeX measurement provides an experimental value for this important line in agreement with an existing extrapolation.

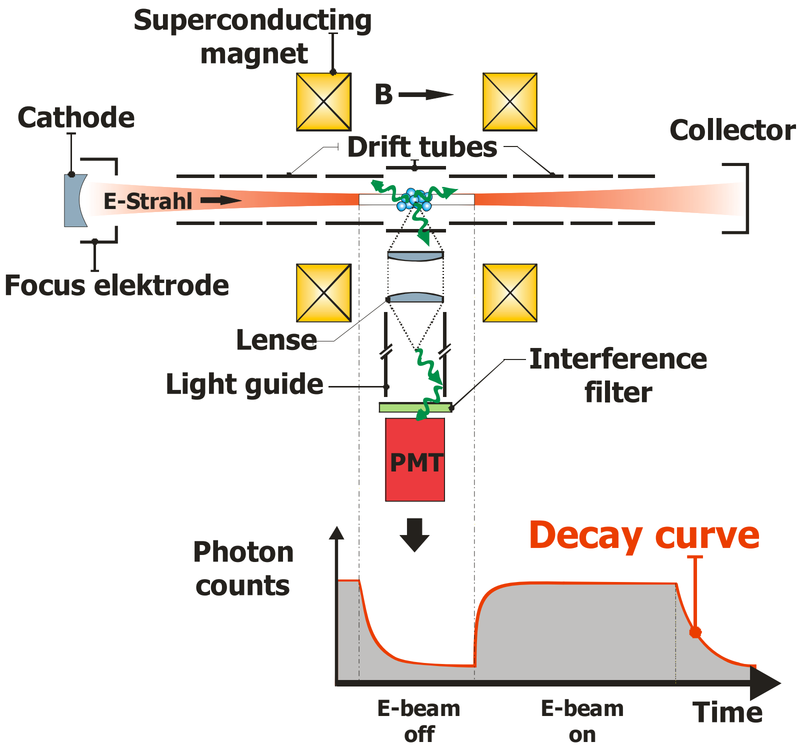

Fig. 1. Sketch of the method used for lifetime measurements in an electron beam ion trap

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MICROCALORIMETER OBSERVATIONS OF L-SHELL SPECTRA OF NE- THROUGH FE-LIKE AU IONS IN AN EBIT

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Reduced-size hohlraums are of interest for generating high-temperature radiation environments. Small hohlraums fill with hot (multi-keV) expanding plasma on the 1-ns timescale of a laser pulse, then partly blocking the hohlraum entrance against further irradiation. Spectral diagnostics based on the L-shell emission of Au are being developed to determine the parameters (temperature, charge balance) of the effluent plasma. For this purpose we have simulated the L-shell emission from highly charged gold ions in the SuperEBIT electron beam ion trap under bombardment by electrons at energies from 10 to 18 keV [1]. The emission was recorded with an x-ray microcalorimeter, featuring an instrumental line width of 10 eV in the region of primary interest. Lines from ironlike Au^{53+} through neonlike Au^{69+} ions were identified. We find that the strong $3d_{5/2} => 2p_{3/2}$ emission features are well separated for at least the highest 13 charge states and can be used to diagnose the charge state distribution. Collisional-radiative calculations relate the observed charge state distribution and the inferred average ion charge $< Z >$ to the electron temperature. Moreover, our calculations indicate a number of density effects that come into play at higher density ; indeed, corresponding line shifts due to the presence of satellite lines can now be recognized in earlier beam-foil spectroscopic observations [2].

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HYPERFINE INTERACTION INDUCED DECAYS IN HIGHLY CHARGED IONS: SUCCESSFUL RADIATIVE DECAY RATE MEASUREMENTS AND SOME PUZZLING PROBLEMS

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In Ni-like ions, the lowest excited configuration is $3d^9$ 4s, and the lowest excitation level, $^3D_3$, can decay to the $3d^{10}$ ground state only by emission of magnetic octupole (M3) radiation. Such high multipole order radiation is of low transition probability at low Z, but it increases steeply with Z. For the ion Xe^{26+}, the predicted level lifetime is about 15 ms. A measurement at an electron beam ion trap at Livermore has determined this value with an uncertainty of only about 1.5 % [1]. In isotopes with a nonvanishing nuclear spin, hyperfine interaction mixes HFS sublevels of the $^3D_3$ level with those of $^3D_2$; the ensuing M3/E2 mixing reduces the lifetime of such sublevels of $^3D_3$. Again, Livermore EBIT measurements on the isotope ^{129}Xe have corroborated specific calculations [2].

Compared to Ni-like ions, Be- and Mg-like ions appear to be much simpler. However, some older calculations of the hyperfine-induced decay rate of the nsnp $^3P^o_0$ [3,4] levels need to be updated, as newer, unpublished, calculations indicate lifetimes that are lower by some 20 %. Two experiments at the heavy-ion storage ring TSR (Heidelberg), one on Be-like Ti^{18+} ions [5], the other on Mg-like ions $^{63,65}Cu^{17+}$ [6], find results that differ by much more (about 40 %) from those vintage expectations. The reason for the discrepancy is not yet understood. At the same time, TSR measurements [6] of the 3s3p $^3P^o_2$ level lifetime in Mg-like Ni and Cu find excellent agreement with recent calculations (our own and [7]), when taking into account M1, E2, M2, and HFS-induced decay channels.

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COMPARISON OF THE EFFECTIVE ELECTRON DENSITY FOR IONS IN DIFFERENT CHARGE STATES IN AN ELECTRON BEAM ION TRAP

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In model calculations simulating the plasma conditions in an EBIT it was assumed [1] and also confirmed experimentally [2] that the electron density, as estimated from the design parameters, is on the order of 10^{13} cm^{-3}. The *effective* electron density was determined from the excitation of several EUV lines of different simultaneously trapped highly charged Fe ions. *Effective* means here that ion-electron collision rate is reduced by the fact that the ions do not dwell all the time within the electron beam diameter. We used a collisional-radiative model to take the mono-energetic electron

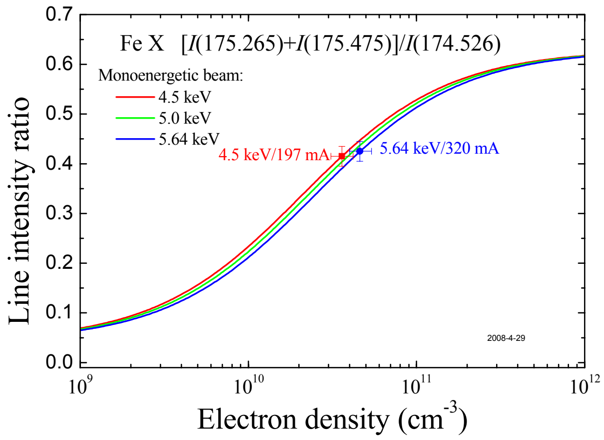

Fig. 1. Intensity ratio I(175.265 Å)/I(175.475 Å) of Fe X vs. effective electron density.

conditions in the EBIT into account. Figure 1 shows the line intensity ratio as a function of the electron density for three Fe X lines. The *effective* electron density under operating conditions of 4.50 keV/197 mA and 5.64 keV/320 mA was 4×10^{10} cm^{-3}, two orders of magnitude smaller than the electron density calculated for that current value and the diameter of the electron beam. We found a value for lines of Fe XXI of 3×10^{11} cm^{-3} under identical conditions. We interpret these differences as a result of the varying overlap between the electron beam and the more extended trapped ion distribution. Indeed, direct observations of the ion distribution in EBITs show that the ion orbits are larger than the size of the electron beam, with ions in high charge states overlapping more strongly with the electron beam than those in lower charge states [2,3]. The present results on *effective* electron densities help to analyze ion production rates within a given set of operating conditions.

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Radiative decay of few- electron ions in the range Z=14 to 54

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Relativistic energies and transition probabilities of the spectral lines arising from states of 2s3p configuration of some selected He-like ions in the range Z= 14- 54 are computed using Multi-configuration Dirac-Fock wave functions in the active space approximation [1,2].Higher order corrections like Breit interaction, self energy and vacuum polarization are also included in the evaluation of transition parameters. To improve the theoretical accuracy of the calculated energies, the quantum electrodynamic (QED) corrections for the 1s2s configuration have been taken from the most recent compilation of Artemyev *et al* [3]. The convergence of the eigenvalues and the effect of configuration mixing of the various virtual shells on the rates have been studied as the active space is being gradually increased [4]. Our calculations show that strong configuration mixing reduces substantially the single configuration allowed E1 rates from He-like ions whereas the trend is irregular for the spin flip dipole rates. To the best of our knowledge, such transitions from ions with empty K shell have not been reported and hence a comparison could not be made.

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QUASIRELATIVISTIC *AB INITIO* STUDY OF GALLIUM-LIKE MOLYBDENUM AND TUNGSTEN

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The quasirelativistic approach, when the relativistic effects accurate up to α^2 are taken into account while solving the equations similar to the Hartree-Fock ones (QRHF), has been created as far back as the seventies. This approach is described in details in the monograph [1] and references therein. The computer code created on the basis of these methods is widely spread. However the detailed analysis of this approach revealed that it was possible to obtain somewhat more precise equations, which allowed one to avoid some oversimplification while solving the equations. Due to this fact the work has been started to create different quasirelativistic approach adjusted for *ab initio* calculations. First it has been proposed to take into account a finite size of the atomic nucleus while solving QRHF equations. For this purpose the model of the charge density distribution inside the nucleus has been created in [2]. This model is appropriate for the applied approach and it allows one to obtain the convenient expansion of the radial orbitals (RO) in the nucleus area. QRHF equations obtained from the Dirac-Fock equations do not require the using of the statistical or model potentials while solving them [3]. The analysis of the solutions obtained for hydrogen-like ions [4] revealed, that it was necessary to take into account the contact interaction with the nucleus while calculating RO not only of s-electrons, but of p-electrons as well [5]. The method of accounting for the virtual excitations when applying the configuration interaction (CI) and the features of the calculations of radial integrals are described in [6]. The implementation of the above mentioned approach allowed us to perform the real calculations of the spectral characteristics of highly charged ions of heavy atoms.

The calculations of the spectral characteristics of Ga-like ions of molybdenum and tungsten have been performed as one of the first examples of the application of the developed quasirelativistic approach. The calculations were performed within CI method. The transformed RO's with variable parameters were used to describe the virtual excitations. The energy spectra, the characteristics of E1-transitions and the radiative lifetimes of $4s^24p$, $4s4p^2$, $4p^3$, 4s4p4d, $4s^24d$, $4s^24f$, 4s4p4f, $4p^24d$ and $4s4d^2$ configurations of Mo^{+11} and W^{+43} have been calculated. The obtained results are in good agreement with the available data.

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THE HYPERFINE QUENCHING OF POLARIZED TWO-ELECTRON IONS IN AN EXTERNAL MAGNETIC FIELD

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The hyperfine quenching (HFQ) in the isoelectronic sequence of He-like highly charged ions (HCI) was successfully used for the determination of the transition probabilities and the fine structure intervals in [1 - 5]. In [6] it was proposed to use the HFQ for observing the parity nonconservation (PNC) effect in He-like Eu. The choice of Eu (Z=63) is determined by the near-crossing of the metastable 2^3P_0 level with the opposite parity 2^1S_0 level and by the inequality $\Gamma(2^3P_0) > \Gamma(2^1S_0)$ where Γ denotes the total width. The latter inequality allows to avoid a huge background effect in the proposed PNC experiment, which assumes the employment of a polarized ion beam. The possible beam polarization method was described in [7]. In the present paper we discuss a method of measuring the beam polarization via the same HFQ mechanism in an external magnetic field. We will show that the HFQ probability in an external magnetic field depends on the beam polarization and this dependence can be measured by standard experimental HFQ techniques [1 - 5]. In the case of the 2^1S_0, 2^3P_0 states with zero total electron angular momentum the ion polarization exists as nuclear polarization. The maximum value of the degree of the nuclear polarization is 93% according to [7]. We should add that polarized ion beams can be used not only for PNC experiments but also for many other purposes, e.g. for testing the time-reversibility [8].

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Hyperfine dependent lifetimes in Neon like ions

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As part of our ongoing investigations of hyperfine dependent lifetimes of metastable levels [1-4] we report on a theoretical investigation of hyperfine quenching in Neon-like ions. The studies were done along the iso-electronic sequence ranging from neutral Ne (Z=10) to Au^{69+} (Z=79). $2p^5 3s\ ^3P_2$ is the first excited level in Ne-like systems and it can only decay to the ground state, $2p^6\ ^1S_0$, through a magnetic quadrupole (M2) transition. For the ions up to $Z \approx 51$, were there is an energy level crossing between the $2p^5 3s\ ^3P_0$ and the $2p^5 3d\ ^3P_0$ level [5], the former is the third excited level and it can only decay to $2p^5 3s\ ^3P_1$ through a magnetic dipole (M1) transition and to $2p^5 3s\ ^3P_0$ through an electric quadrupole (E2) transition. Also it has no possibility to decay to the ground state except through a two-photon decay. In the presence of a nuclear spin though, the hyperfine interaction introduce a small mixing of $2p^5 3s\ ^3P_1$ and $^1P_1$ into $2p^5 3s\ ^3P_2$ and $^3P_0$ respectively, opening up hyperfine induced electric dipole (hpf-E1) transition channels to the ground state for both of the metastable levels.

Extensive multiconfiguration Dirac-Hartree-Fock calculations were performed to calculate the transition probabilities for the various transitions from the two metastable levels as well as the transition matrix elements of the $2p^6\ ^1S_0 - 2p^5 3s^3P_1$ and the $2p^6\ ^1S_0 - 2p^5 3s^1P_1$ E1 transitions. Also the off-diagonal hyperfine interaction constants between the metastable levels and the $2p^5 3s\ ^3P_1$ and the $^1P_1$ levels were calculated. First order perturbation calculation were used to calculate the $2p^6\ ^1S_0 - 2p^5 3s\ ^3P_2$ and the $2p^6\ ^1S_0 - 2p^5 3s\ ^3P_0$ hpf-E1 transition rates and the hyperfine dependent lifetimes of the hyperfine levels of the metastable levels. It is shown that the $2p^5 3s\ ^3P_2$ level is sensitive to hyperfine interaction all along the iso-electronic sequence ranging from Z=10 to Z=79. It is also shown that the $2p^5 3s\ ^3P_0$ level is very sensitive to the hyperfine interaction in the beginning of the iso-electronic sequence where the hpf-E1 transition, in many cases, are orders of magnitude larger than the M1 and E2 transition rates. This sensitivity decreases with Z since both the M1 and the E2 transition channels have a higher order of Z dependence compared to the hpf-E1 transition channel. However even for highly charged ions, if the nuclear magnetic dipole moment is large, the hyperfine quenching can have a substantial influence on the lifetime of the $^3P_0$ level. An example is the hyperfine quenching of $^3P_0$ in In^{39+} which is lowering the lifetime by about 25%.

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QED CALCULATION OF INTERELECTRON INTERACTION CORRECTIONS FOR TRANSITION PROBABILITIES IN TWO-ELECTRON IONS

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We present *ab initio* QED calculation of the transition probabilities for two-electron ions with nuclear charge numbers $Z = 10 - 92$. Employing the line profile approach [1], higher orders of interelectron interaction corrections are taken into account. The radiative corrections were not considered. In particular, calculations are performed for nondegenerate levels $(1s2s)\,^3S_1$, $(1s2p_{3/2})\,^3P_2$ ($M1$ and $M2$ transitions, respectively) and for quasidegenerate levels $(1s2p)\,^1P_1$, $(1s2p)\,^3P_1$ ($E1$ transitions), decaying to the ground state $(1s1s)\,^1S_0$. Both the “velocity” and “length” gauges for describing the emitted photons are considered.

This is the first exact QED calculation of the transition probabilities for the quasidegenerate levels. In the case of quasidegenerate levels the standard QED perturbation theory has a slow convergence for ions with the nuclear charge $Z < 50$. There is a necessity to take into account the higher-order interelectron interaction corrections. Within the framework of the line profile approach we developed a special technique to evaluate the higher-order interelectron interaction corrections to the transition probabilities. One- and two-photon exchange Feynman graphs are considered. The QED perturbation theory applied here is eligible for further improvement of the accuracy of calculation order by order. Calculating the contribution of the interelectron interaction, the QED radiative corrections to the transition probabilities for the quasidegenerate levels become also relevant.

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The RESONANT STATES of LIII BETWEEN THE N=2 AND 3 THRESHOLDS

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Doubly excited states of two-electron atom and ions have attracted physicists to study experimentally and theoretically. The doubly excited $^1P^o$ resonant states of Li^+ have been observed firstly by Dual Laser Plasma technique[1]. After high-resolution monochromators at synchrotron-radiation facilities have been developed, high-resolution measurements on Li^+ ion were performed at the Advanced Light Source[2] and Super-ACO[3]. Recently, absolute cross-section measurements for the double photoexcitation of Li^+ ion have been performed by using the photo-ion merged-beam endstation. Accurate measurements on several members of the ($_2(0,1)^+_n$, $_3(1,1)^+_n$) $^1P^o$ Li^+ ion have been made[4,5]. On the theoretical side, some resonances have been studied by the R-matrix method[4,5] and saddle-point complex rotation method[6].

In the present work, we studied lowest five doubly excited $^1P^o$ resonant states of Li^+ between the N=2 and 3 thresholds by saddle-point complex rotation method with B-spine functions. In a Configuration Interaction scheme, we constructed the wave functions in terms of B splines of order k and total number N, defined between two end points, r_{min}=0 and r_{max}= R, and built vacancies into the wave functions. By saddle-point variation method, we obtained the saddle-point energies and wave functions. After the saddle-point variation is carried out, we calculate the resonance energies and widths by a complex-rotation method. In the present, the values of R for end points are chosen to be 400 a.u. so that the saddle-point energies are converged to within uncertainty of 10^{-8} a.u. We included 10 partial waves at least in calculating the resonant sates of Li^+ to ensure the saddle-point energies converged within uncertainty of 10^{-8} a.u. For each partial wave, our results converged to within 10^{-8}. a.u. with increasing order k and total number N of the B spline. We also calculated the expectation value of the angle between the two electrons, θ_{12} ,the average value of r for the inner electron and outer electron, $r_<$, $r_>$, and the average values of r and r^2. The doubly excited states are grouped in Rydberg series labeled by the quantum numbers K, T, A. For lowest five $^1P^o$ resonant states, there are two members in the $_3(1,1)^+_n$ series, one member in the $_3(2,0)^-_n$, $_3(-1,1)^+_n$ and $_3(-1,0)^-_n$ series.

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OBSERVATION AND MODELING OF HOLLOW MULTICHARGED IONS X-RAY SPECTRA RADIATED BY LASER PRODUCED PLASMA.

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Plasma of multicharged ions (Z =10 – 20) with the electron temperature 10 – 100 eV and the electr on density 10^{22} – 10^{23} cm^{-3} is produced usually by interaction of a high-contrast femtosecond laser pulses with solids or clusters. The same plasma parameters are also realized when nanosecond shor t-wavelength laser pulses (KrF or XeCl or 3d, 4^{th} harmonics of Nd glass lasers) interact with the sol ids. Highly charged ions plasma with such parameters is already weakly- coupled and it is very inte resting to investigate radiation property of it. It has been shown in [1-5] that the X-Ray emission sp ectra of such plasma contain some exotic spectral lines caused by radiative transitions in the so call ed "hollow ions", that are the highly charged ions with an empty inner K-shell.

In the present work the role of hollow highly charged ions to the X-Ray emission spectra is investigated for 2 cases: 1) plasma obtained under irradiation of Ar clusters by ultrashort laser pulses and 2) Mg-plasma heated by a short-wavelength long-pulse (nanosecond) laser.

For the first case, cluster-gas targets were irradiated by short laser pulses with various intensities, durations and contrasts. Calculations in support of these measurements have been performed using a detailed atomic kinetics model with the ion distributions found from solution of the time-dependent rate equations. The calculations are in reasonably good agreement with the measurements and the role of hollow highly charged ions in the resulting complicated spectra is analyzed. It is demonstrated that, although the presence of hollow atoms is estimated to add only around 2% to the total line emission, signatures of hollow atom spectra can be identified in the calculations, which are qualitatively supported by the experimental measurements.

In the case of long-lived plasma, produced by XeCl laser irradiation of solid Mg target, clear signatures of transitions from hollow ions are observed in the experimental spectrum. Spectra were identified from large-scale atomic kinetics calculations using the recently developed mixed-UTA (MUTA) model [6]. The relative strength of hollow ion spectral lines is explored and the temperature and density regions in which they are produced are analyzed. Large density and temperature gradients are required to simulate the observations, and additional influence to the hollow atom spectra were simulated with using a hot electron component in the electron distribution function

The kinetic simulations were made with collisional rates calculated in the isolated-atom approximation. The relatively good agreement between theoretical and experimental spectra means that use of such an approximation for the description of the collisional processes is justified for weakly-coupled plasma with the electron-ion coupling factor $\Gamma_{ei} < 1$.

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A TALE OF TWO LINES IN PROMETHIUM-LIKE ION SPECTRA

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Highly charged ions in the promethium sequence (61 electrons) have been suggested to show spectral features resembling the alkali sequence ions [1,2]. Guided by calculations, the possibly prominent 5s - 5p resonance lines have been sought in a variety of experiments, ranging from laser-produced plasmas, beam-foil spectroscopy [3,4], ion-atom collisions to electron beam ion traps [4] and tokamaks [5], and from W (Z=74) to U (Z=92). Most of the experiments, however, did not find any prominent lines as would be typical for alkali-like systems, and several earlier claims of identification are not substantial enough to be accepted. With the most extensive calculations of Pm-like ions available now [6], applying relativistic multi-reference Møller-Plesset second-order perturbation theory, the experimental evidence is reviewed, and options for a sensitive search are explored. The 5s and 5p levels are the lowest of their respective symmetries only for very heavy ions, and therefore it is only in those ions that any alkali-like signature may be found in the spectra. However, the ionization potentials of the ions of interest are so low that any existing EBIT could be used.

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LINE EMISSION FROM M-SHELL TITANIUM IONS

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We have investigated the M-shell emission from highly charged titanium ions. The spectral lines of interest from Ti^{4+} through Ti^{7+} fall between 240 and 280 Å. The emission was measured with a grazing-incidence flat-field spectrometer described in ref. [1] using a 1200 lines/mm variable line spacing spherical Hitachi grating and a 100 μm slit. The R = 5.6 m EUV instrument has a wavelength resolution of about 0.3 Å FWHM and can cover the 25 - 450 Å range. A cryogenically cooled back-illuminated Photometrics CCD camera was used as the detector.

The emission lines were observed in the SSPX spheromak [2] at the Lawrence Livermore National Laboratory. The SSPX hydrogen plasmas had densities of a few times 10^{14} cm^{-3} and achieved temperatures from 10 eV up to over 500 eV, corresponding to titanium charge states up to neon-like Ti^{12+}. Titanium was confirmed as an intrinsic ion impurity in the spheromak by injecting atomic titanium into the machine and thus enhancing specific spectral features.

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EUV SPECTRA FROM HIGHLY CHARGED TIN IONS OBSERVED IN LOW DENSITY PLASMAS IN LHD

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Recently the needs for experimental databases of extreme ultraviolet (EUV) spectral lines from highly charged tin (Sn) ions have grown in connection with high density tin plasmas as a promising candidate for the light source around 13.5 nm for the semiconductor lithography process. On the other hand, low density plasmas generated in magnetically confined devices for fusion research are more suitable to meet the needs for the databases because they are optically thin and have relatively mild temperature and density gradients which are easily controlled.

In this study, we have measured EUV spectra (11–15 nm) from highly charged tin ions in the low density plasmas produced in the Large Helical Device (LHD) at the National Institute for Fusion Science. A small amount of tin was introduced into a background high temperature ($\simeq$1000 eV) and low density ($\simeq 10^{19}$ m^{-3}) hydrogen plasma by injecting a tracer encapsulated solid pellet (TESPEL). The EUV spectra were monitored by a grazing incidence spectrometer SOXMOS [1] whose absolute wavelength was calibrated with the accuracy of 0.02 nm by using allowed transition lines of iron ions.

Spectral feature of the unresolved transition array (UTA) around 13.5 nm according to 4d–4f transition of tin ions has been clearly observed after the plasma is sufficiently cooled due to the pellet injection. The comparisons with the other experimental data [2,3] indicates that the dominant ionization stages for this feature are from Sn^{11+} to Sn^{13+}, which would correspond to the electron temperature around 50 eV assuming the coronal ionization equilibrium. However, the actual electron temperature measured by a Thomson scattering diagnostic is much higher (300–400 eV) at the point of the pellet ablation, which implies that the plasma lies far from the ionization equilibrium.

Besides the lines from Sn^{11+} to Sn^{13+} ions, we have observed several sharp lines in 13.8–14.6 nm which are similar to the charge exchange collision spectra [3] from much highly charged tin ions. The validity of this speculation will also be discussed based on the dependence of these line intensities on the electron temperature and the comparisons with theoretical calculations.

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