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High-Resolved X-ray Spectra of Hollow Atoms in a Femtosecond Laser-Produced Solid Plasma

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Abstract

A new type of quasi-continuous spectra of femtosecond laser plasma in the vicinity of multicharged H-like and He-like ion resonance lines were observed and interpreted for the first time. It is shown that such spectra were generated by multicharged hollow ions and are caused by super high density conditions provided by a high contrast laser pulse.

1. Introduction

X-ray spectra of nano- and subnanosecond laser produced plasmas were intensively investigated during the last 20 years. In particular the spectral features of radiation in the vicinity of H-like and He-like resonance lines of highly charged ions were studied in detail. The spectra in this region have a typical structure characterized by the presence of satellite lines originating from the autoionizing states. E.g. the He-like satellites $2l2l'$ of H-like Ly_α and the Li-like satellites $1s2l2l'$ of the He-like resonance line $1s2p\ ^1P_1 - 1s^2$ are often used for diagnostic purposes. Collisional radiative models provided with atomic data and spectral profiles were widely recognized and used in plasma experiments (see, for example, reviews [1,2] and works [3–5]).

X-ray radiation from laser plasmas created by pico- as well as subpicosecond lasers became a subject of investigations in recent years. The spectral features of this radiation occurred to be quite similar to that observed earlier in the same region with longer pulses. Measured spectra resembled the standard shape reproduced by coronal models while the variations of line intensities are described by the changes of plasma parameters: electron temperature and density [4–13], presence of hot electrons [4,5,9]. It is important to underline here that in the problem of short laser pulses interaction a substantial role is played by the creation of a preplasma connected with the presence of a laser prepulse. Present experiments carried out with femtosecond lasers characterized by super high contrast (pulse/prepulse intensity ratio) of order 10^{11} [14,15] revealed a new type of spectra not observed before in this spectral region. It is shown that the observed spectra of a new type can only be interpreted by accounting for the radiation generated at high electron densities from multicharged ions with vacancies of one and two (so called hollow ions) electrons in the K-shell.

2. The experimental setup and results

The experimental investigations were carried out both on the TRIDENT laser facility in Los Alamos National Laboratory [14,15] and on the laser facility in the Center for Ultrafast Optical Science at the University of Michigan [16]. In the first case the laser pulse had a duration of 500 fs, an energy of 550 mJ and peak intensities in the range of $(0.5–1) \times 10^{19}$ W/cm^2. The power contrast between the main pulse and the naturally occurring nanosecond time scale prepulse was at least 10^{10} to 10^{11}. Solid Si targets were used. In the second case the laser pulse had a duration of 400 fs, an energy of up to 2 J and about the same peak intensity and power contrast. Solid Mg, Al and S targets were used. In some experiments a laser prepulse with a duration of 100–150 ps and an energy of 0.02–2 J was used to study the interaction of the main laser pulse with a preplasma, instead of with solid substance.

X-ray plasma emission have been observed by means of spectrographs with spherically bent mica crystals. Crystals with radii of curvature equal to 100, 150 and 186 mm have been used. The crystals, plasma and photographic film (or X-ray CCD) were placed according to the FSSR-1D and FSSR-2D schemes [2,17]. This allowed to have simultaneously high spectral ($\lambda/\delta\lambda \approx 10.000$) and spatial ($\delta x \approx 10$ μm) resolutions. Examples of spectra obtained are presented in Figs. 1, 2.

It can be seen from these figures that unusual spectra in distinction to familiar ones consist of much more developed spectral structure of a quasi-continuous character merging with the main reference lines. Theoretical spectra calculated in the framework of the widely used coronal quasi-steady-state plasma model (resembling the typical spectra observed for low contrast laser-produced plasma) fail to describe the spectral features when a high contrast femtosecond laser pulse was used for plasma creation. A physical reason for such drastical spectra restructuring could be naturally attributed to a difference in mechanisms of plasma production. The absence of a preplasma leads to a direct interaction of the ultra-short laser pulse with solid substance resulting in the creation of much higher electron densities. At such densities numerous lines not developed

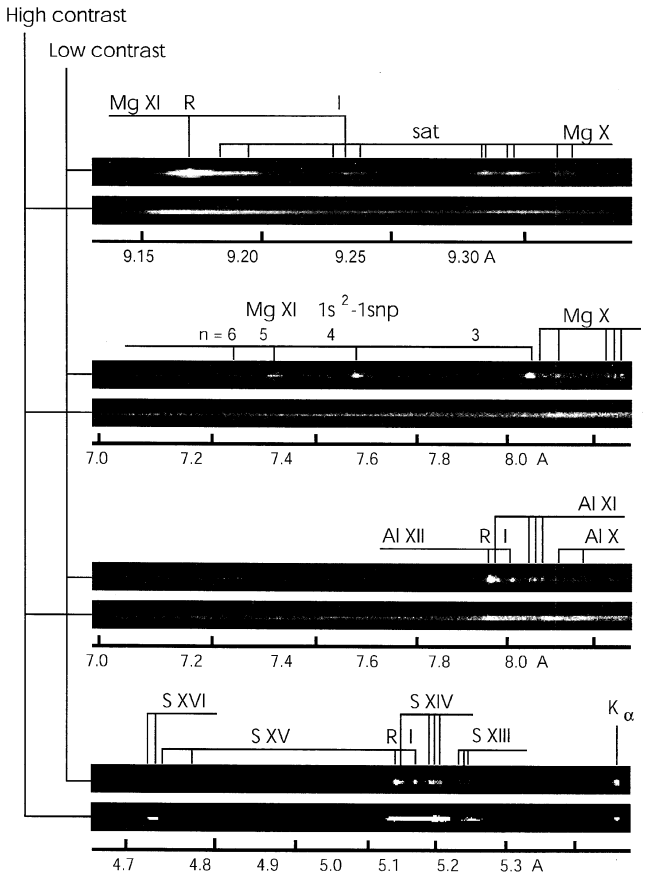

Fig. 1. Emission spectra of magnesium, aluminum and sulfur plasma, heated by a femtosecond laser pulses with high (without prepulse) and low (with prepulse) contrast.

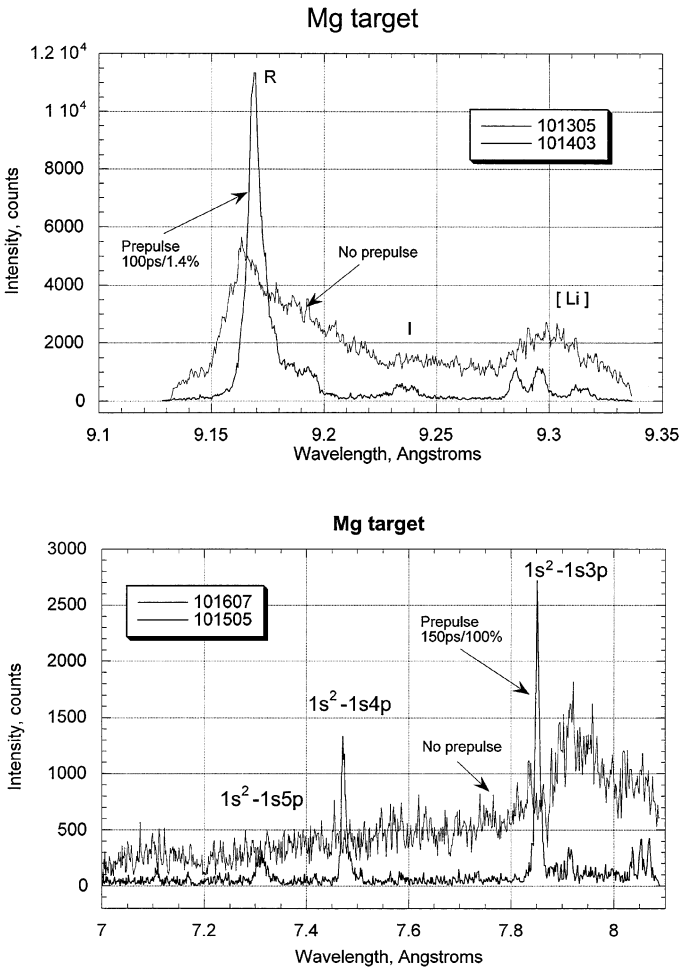

Fig. 2. Densitograms of spectra radiated by magnesium femtosecond laser-produced plasma.

at the coronal conditions became dominant in the spectra [14,15].

The observed spectra of a new type could only be interpreted by accounting for the radiation generated at high electron densities from multicharged hollow ions, i.e. ions with an empty K-shell. Such neutral and quasi-neutral species (hollow atoms) were firstly observed in ion-surface interaction experiments [18]. Structures of analogous type for multicharged ions were observed recently in spectra measured near the target of laser plasma created by smoothed Nike ns laser irradiation [19].

The atomic spectra calculations made with the help of HULLAC and SUPERSTRUCTURE codes show that the spectral regions under study are covered by numerous lines originating from transitions in multi-electron systems with a number of electrons $q \geq 3$ (Li-, Be- like ions) with empty K-shell (see Fig. 3). The population of hollow ion states with $q \geq 3$ in a plasma at coronal conditions are negligibly small and the spectra of the type as given in Figs. 1, 2 (low contrast case) are produced by He-like ions. In a superdense plasma with electron density N_e exceeding the critical value N^* (for example, for Si plasma N^* is about 10^{22} cm^{-3}) nonlinear effects in the population densities lead to a considerable increase of hollow ion populations and hence the intensities of corresponding lines (see Figs. 1, 2, high contrast case). It is worth pointing out important consequences of these effects: (*i*) the collisional mixing over *l*-subshells results in widely spread spectral structures characterized by the principal quantum number n, and (*ii*) the increasing role

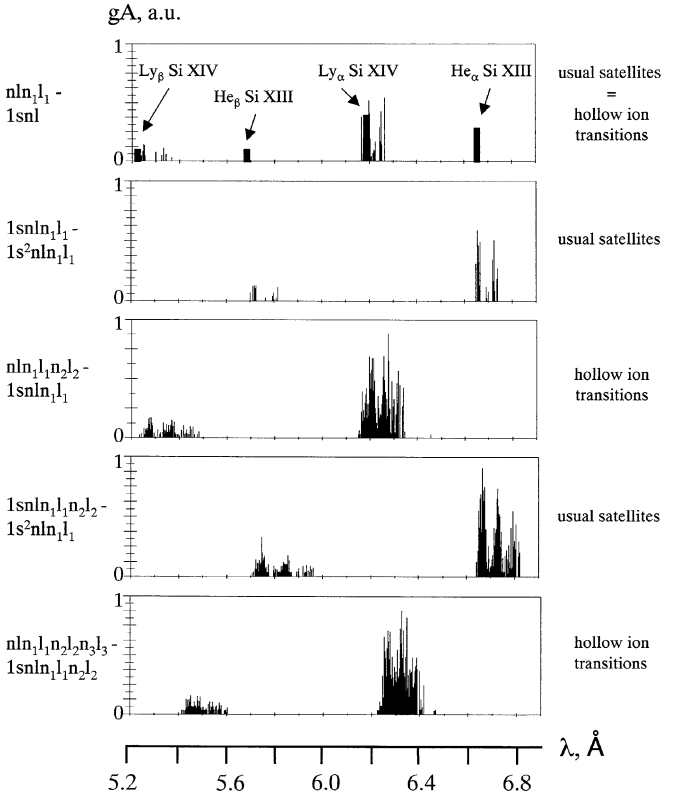

Fig. 3. Radiative transitions calculated by HULLAC code for He-, Li-, Be-like Si ions with one and two vacancies into a K-shell (n,n_1,n_2,$n_3 = 2, 3$).

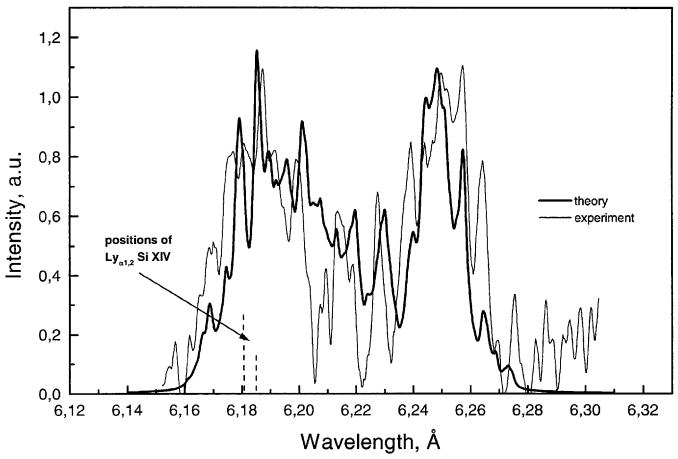

Fig. 4. Comparison of emission spectra of silicon femtosecond laser plasma in the vicinity of H-like Si XIV Ly$_\alpha$ line ($\lambda = 6.182$ Å) with calculations based on SUPERSTRUCTURE atomic data.

of additional mechanisms in population of the states with $q \geq 3$ such as dielectronic capture from excited states [10] and three-body recombination [9].

It is possible to describe observed spectra by using a simple kinetic model [12,15] for the distribution of relative population densities over hollow ion complexes. The example of a composed spectrum is given in Fig. 4. It indicates a reasonable agreement with experimental data. Thus the quasi-continuous spectra of a new type revealed in femtosecond laser plasma created by a high contrast pulse are really generated by multi-charged hollow ions, and such plasma can be used as a natural source of hollow atoms providing a new possibility for the study of their properties. At the same time the presence of ionic states with empty K-shell is a manifestation of super high densities leading to the break down of coronal conditions in the plasma.

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References

1. Boiko, V. A. *et al.*, J. Sov. Laser Research **6**, 85 (1985).
2. Skobelev, I. Yu. *et al.*, J. Exp. Theor. Phys. **81**, 692 (1995).
3. Faenov, A. Ya. *et al.*, Phys. Rev. **A 51**, 3529 (1995).
4. Rosmej, F. B., J. Phys. B. Lett. **30**, L819 (1997).
5. Glenzer, S. H. *et al.*, Phys. Rev. Lett. **81**, 365 (1998).
6. Rosmej, F. B. *et al.*, J. Phys. B. Lett. **29**, L299 (1996).
7. Rosmej, F. B. and Faenov, A. Ya., Physica Scripta, **T73**, 106 (1997).
8. Rosmej, F. B. *et al.*, J. Exp. Theor. Phys. Lett. **65**, 708 (1997).
9. Rosmej, F. B. *et al.*, J. Quant. Spectrosc. Radiat. Transf. **58**, 859 (1997).
10. Rosmej, F. B. *et al.*, J. Phys. B. Lett. **31**, 921 (1998).
11. Rosmej, F. B. *et al.*, J. Quant. Spectrosc. Radiat. Transf., 1999.
12. Rosmej, F. B. *et al.*, Physica Scripta, this issue.
13. Rosmej, F. B. *et al.*, J. Phys. B. Lett., 1999.
14. Faenov, A. Ya. *et al.*, Proceedings of SPIE 97, **3157**, 10 (1997).
15. Urnov, A. M. *et al.*, J. Exp. Theor. Phys. Lett. **67**, 489 (1998).
16. Pikuz, S. A. *et al.*, J. Exp. Theor. Phys. Lett., **66**, 481 (1997).
17. Young, B. K. F. *et al.*, Rev. Sci. Instrum., **69**, 7049 (1998).
18. Briand, J.-P. *et al.*, Phys. Rev. Lett. **65**, 159 (1990).
19. Aglitsky, Y. *et al.*, Phys. Plasmas **3**, 9 (1996).