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High Resolution Spectral Features of the Hollow Ions and Inner-Shell X-Ray Emission Produced by 10^{-4} - 10^{-10} Contrast Femtosecond-Pulse Laser Irradiation of Argon Clusters

コントラスト比 10−4〜10−10 のフェムト秒レーザーとアルゴンクラスターの相互作用により生成される中空イオンと内殻 X 線放射の高分解能スペクトル線の特長

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A study is made of the ultra-short laser pulse irradiation of Ar cluster targets. Experiments have been performed with large cluster sizes and using very high laser contrasts, which have allowed clear and unambiguous observation of exotic inner-shell transitions in near-neutral Ar ions. The interaction of the main laser pulse with the unperturbed target is a necessary requirement for observing these lines. Our measurements are supported by kinetics calculations in which a very detailed atomic model is used. The calculations predict all of the spectral features found experimentally, and support the notion that the X-ray emission arises from many ion stages of the Ar plasma, from near-neutral through He-like ions, and from a range of plasma temperatures and densities. X-ray spectral methods have been proposed to determine the parameters of the plasma formed at the early stages of its evolution. It has been shown that the spectra of hollow ions are the most informative in the first moments of the heating of a cluster, whereas the diagnostics of the late stages can be performed using the conventional lines of multicharged ions.

1. Introduction

The use of clusters as targets for high-power ultra-short laser pulses is an active area of research. Cluster targets absorb laser pulse energy more efficiently than gas or solid targets, and so have the potential to create high-density plasmas. Previous studies [1], as illustrated in Fig.1, have found that in the case of using micron clusters of Ar, irradiated by 30 fs Ti:Sa laser pulses with relativistic intensities of > 10^{18} W/cm^2, a change in contrast from of ~ 10^{-2} to 4×10^{-6} can noticeably change the ionization balance of Ar. Fs laser pulses with a super-high contrast of ~ 10^{10} have recently become available and used in our investigations of radiation properties of clusters, irradiated by such laser beams.

2. Experimental set up.

A Ti:Sa CPA laser system J-KAREN with energy of ~ 1 J, pulse duration of ~ 40 fs was focused in the spot size of ~ 30 μm, which corresponds the maximum of laser intensity on the Ar cluster targets of 3.5×10^{18} W/cm^2. Using OPCPA approach, an additional Pokkels cell and saturable absorber, the contrast of the prepulse to the main laser pulse has been improved up to 10^{-10}. The laser contrast can also be decreased by up to 10^{-8} by switching off the Pokkels cell and saturable absorber. Ar gas at the reservoir pressure 60 MPa was expanded through specially designed nozzle [2] and Ar clusters with the mean size of ~ 1.5 μm is produced. The spatially resolved X-ray spectra were measured with spectral resolution $\lambda/\delta\lambda$ > 3000 using focusing spectrometers with spatial resolution (FSSR-1D) and back illuminated X-ray CCD as a detector. Typical X-ray spectra of He-like Ar spectra are presented in Fig. 2.

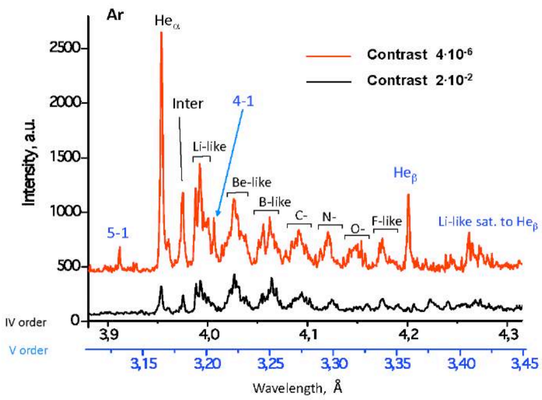

Fig. 1. Variation of the observed emission spectra with the low and medium laser contrasts

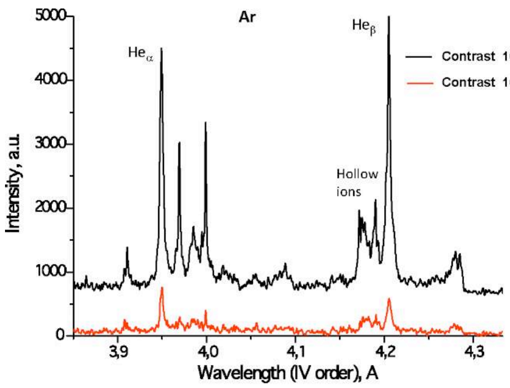

Fig. 2. Variation of the observed emission spectra with the high laser contrast.

2. Experimental results and discussions.

First of all, we find that for spectra obtained with a higher contrast the satellite spectral lines in the range 4.0 to 4.15 Å, which belong to lower-charged ions (B-, C-, N-, O-, F-like Ar) are weaker. At the same time, the intensity of lines arising from transitions in He-like ions is increased. Such behavior is similar to previous findings [1] which observed similar trends when the laser contrast was increased from 10^{-2} to 10^{-6}. We also observe new, very pronounced structures near the K_α lines of Ar, which are belong to KL Hollow ions (see Fig. 2). With increasing laser pulse duration for both positive and negative directions, the total intensity of spectra in the vicinity of the He_α line of Ar is decreased (and is more intense for negative laser pulses). At the same time, the intensity of the Hollow ions spectral lines relative to the intensities of all other lines arising from He-like ions clearly grows for longer pulse duration, especially for negative chirp laser pulse duration.

The modeling of Ar spectra was made by use of the Los Alamos suite of atomic physics codes [1]. The results of such modeling and comparison them with experimental spectra are presented in Fig.3 and demonstrated that the main observed spectral are formed at quite different times. The KL Hollow ions spectra arise near the beginning of the main pulse interaction with the cluster, at temperatures around 10 - 20 eV and high electron densities between 10^{22} - 10^{23} cm^{-3}. A significant hot electron component is present at these early times. The more usual Li-like through O-like satellites, and high-n transitions of He-like Ar ions, are formed at slightly later times when the electron temperature grows to 100 - 500 eV and the electron density decreases to around 10^{21} - 10^{22} cm ^{3}. The hot electron influence on these lines is still considerable. At later times (~ 1 ps) contributions to the He_α and intercombination lines increase, when the temperature exceeds 1 keV

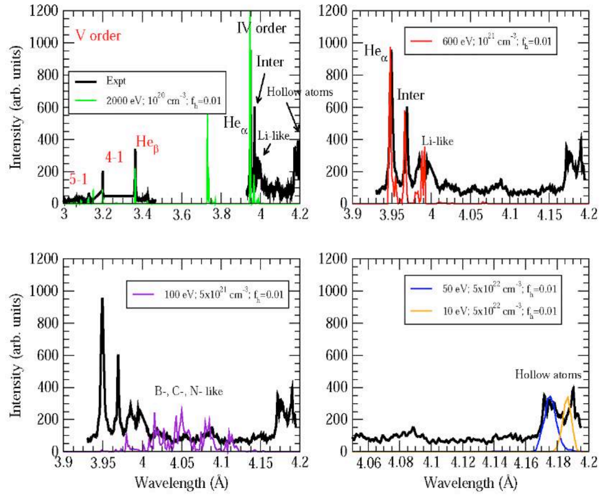

Fig. 3. ATOMIC calculations compared to the measured spectra of Fig. 2. The upper-left panel shows ATOMIC FS calculations at a temperature of 2 KeV and electron density of 10^{20} cm^{-3} and the upper-right panel shows ATOMIC FS calculations at a temperature of 600 eV and density of 10^{21} cm^{-3}. The lower - left panel shows ATOMIC MUTA calculations at a temperature of 100 eV and electron density of $5x10^{21}$ cm^{-3}, and the lower - right panel shows ATOMIC MUTA calculations at temperatures of 10 and 50 eV and at electron densities of $5x10^{22}$ cm^{-3}. All calculations include a 1% hot electron component.

and the density drops to around 10^{20} cm^{-3}.

If to conclude, the very high contrast of the ultra-short J-KAREN laser pulse used in our experiments has allowed to measure spectra, which containing features arising from neutral Ar through He- like Ar, underlining the richness of the dynamical processes which occur when intense ultra-short laser pulses are focused on gas cluster targets. For modeling such complicated spectra, it was found that a detailed NLTE atomic model is required, which includes collision processes spawned by highly energetic electron fractions. Our investigations show that the spectral lines of He-like ions and their satellites, including spectral lines from Hollow ions can be used for the diagnostics of the plasma parameters at the different stages of ultra-short laser interaction with clusters.

Acknowledgments

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