27. Production of Highly Charged Ions of Argon by Optical Field Ionization in a Relativistic Laser Field

Akito SAGISAKA, Yutaka AKAHANE, Makoto AOYAMA, Fumihiko NAKANO, Koichi YAMAKAWA

Advanced Photon Research Center, Kansai Research Establishment,
Japan Atomic Energy Research Institute
8-1 Umemidai Kizu-cho, Kyoto 619-0215 Japan

We observed the highly charged ions of argon by optical field ionization in a relativistic intensity regime. Charge states up to Ar^{15+} were produced at the highest intensity of 800 nm, linearly polarized 20 fs Ti:sapphire laser pulses. The peak intensity of the pulse is determined by comparing the measured ion production curve for Ar^{9+} with ADK theory. The results of these measurements of the ionization indicate that the maximum peak intensity is achieved to $\sim 2\times 10^{19}$ W/cm^2.

Keywords : Optical field ionization, Relativistic, Highly charged ion, ADK theory

1. Introduction

The ultrafast, ultrahigh-peak power laser systems can realize pulses with a peak intensity of $>10^{19}$ W/cm^2 at many hertz [1, 2]. Such high intensity ultrashort laser pulses are useful for the variety of high-field applications such as the generation of ultrafast x-ray radiation [3] and high harmonic generation [4] from solid targets. In high-field physics experiments, the peak intensity is one of the most important issues for studying light-matter interaction in the relativistic regime. In general, a focused intensity can be estimated by measuring the energy, pulse duration, and spot size of the laser pulse. This estimation, however, is uncertain by a factor of 2-3, because the full energy in the experiment is not always concentrated in the central portion of the spatial and temporal profiles. A more direct measurement is required in order to determine the actual peak laser intensity.

The effective peak intensity can be determined from the ionization rate of Ammosov-Delone-Krainov (ADK) tunneling ionization theory [5]. Ionization in a strong laser field has been investigated extensively for many gases and various wavelengths and the intensity dependence of the ion yield has been observed and compared with the calculated dependence below 10^{18} W/cm^2 [6 - 8]. Augst et al. reported experimentally that the observed ion-production curves of noble gases agree with curves predicted by ADK theory and barrier suppression ionization [8]. Walker et al. recently reported that Ar^{16+} is observed at the peak intensity of 5×10^{19} W/cm^2 [2]. Electrons oscillating in such an ultra-intense laser field are relativistic and thus this makes it possible to investigate an entirely new class of physical effects such as relativistic self-focusing of the laser pulse [9] and harmonic generation by relativistic electrons [10] in the ultrahigh-intensity laser field. Therefore, accurate comparison of the ion yield with ADK theory is more important in the relativistic intensity region (> 10^{18} W/cm^2).

In this paper, we determine the laser peak intensity by optical field ionization of highly charged argon ions. Using the peak intensity at which Ar^{9+} occurs as a base, we can characterize the peak intensity of over 10^{19} W/cm^2 from the energy scaling of the laser pulse.

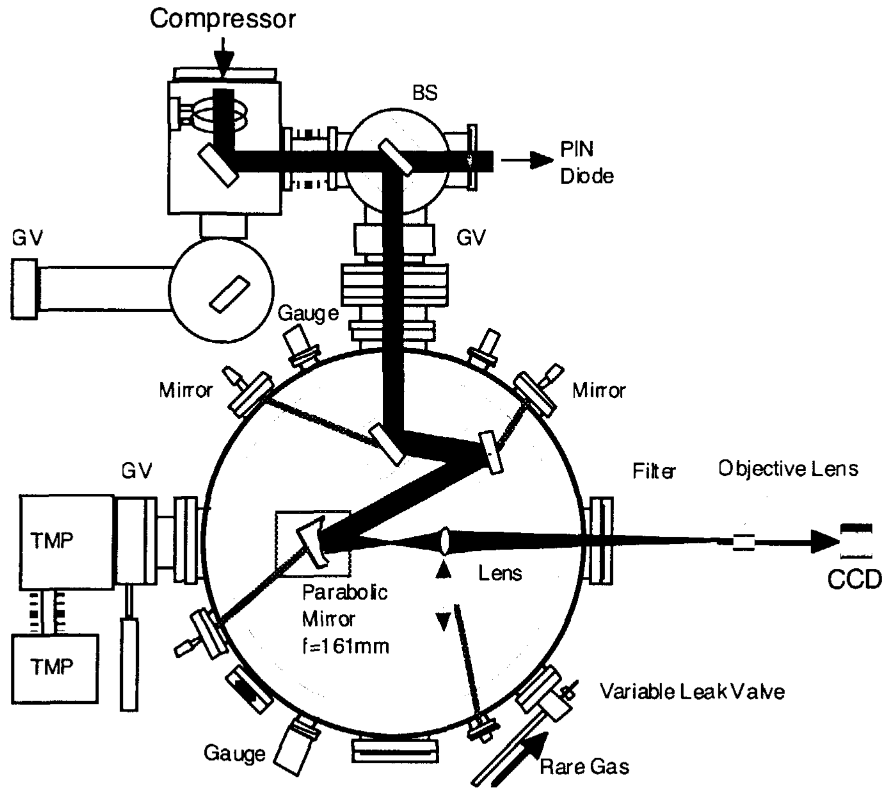

Fig. 1 Experimental setup. BS: beam splitter, TMP: turbomolecular pump, GV: gate valve.

2. Experiment

A Ti: sapphire laser system developed at our Institute [1] was used to the atomic photoionization experiments. The maximum energy and the pulse duration were measured to be 100 mJ and 20 fs, respectively. The details of this laser system are described in Ref. 1. The experimental setup is shown in Fig. 1. The laser pulse from the vacuum pulse compressor was transported in the interaction chamber. After that, the linear polarized laser light was focused by an off-axis parabolic mirror (f = 161 mm). The diameter of the focal point of the attenuated laser beam was analyzed by an objective lens associated with a charge-coupled device (CCD) camera (COHERENT: COHU6400). We found a typical full width at half maximum (FWHM) of the spot was 6.8 μm. The spatial profile and temporal shape were assumed as Gaussian. The peak intensity was estimated as $0.78\,E/(\tau \pi r^2)$, where E is the laser energy, τ is the pulse duration at FWHM, and r is the spot radius at half width at half maximum (HWHM). Based on these optical measurements, the peak intensity was estimated to be 1.1×10^{19} W/cm^2.

For the ionization experiments, the ion signals were measured with a time-of-flight (TOF) mass spectrometer having a 93 cm drift tube [11]. A turbomolecular pump evacuated the chamber to below 10^{-8} Torr. The argon gas pressure in the interaction chamber was controlled by a variable leak valve and ranging from 10^{-7} to 10^{-4} Torr. The purity of argon gas was better than 99.999%. Ions were generated at the focal point in the interaction chamber and detected at the end of TOF tube with a two-stage microchannel plate (MCP, Hamamatsu: F4655-12) or an electron multiplier tube (EMT, Hamamatsu: R5150-10). The MCP was a high-speed type with a rise time of 400 ps. A mass gate deflector with a pulsed voltage (TOYAMA: THV-01M) in the drift tube was used to avoid the detector saturation. The temporal profile of the ion yield detected by the MCP or by the EMT was recorded by a digital oscilloscope (Tektronix: TDS644B) or an ion counter (Stanford Research Systems: SR430).

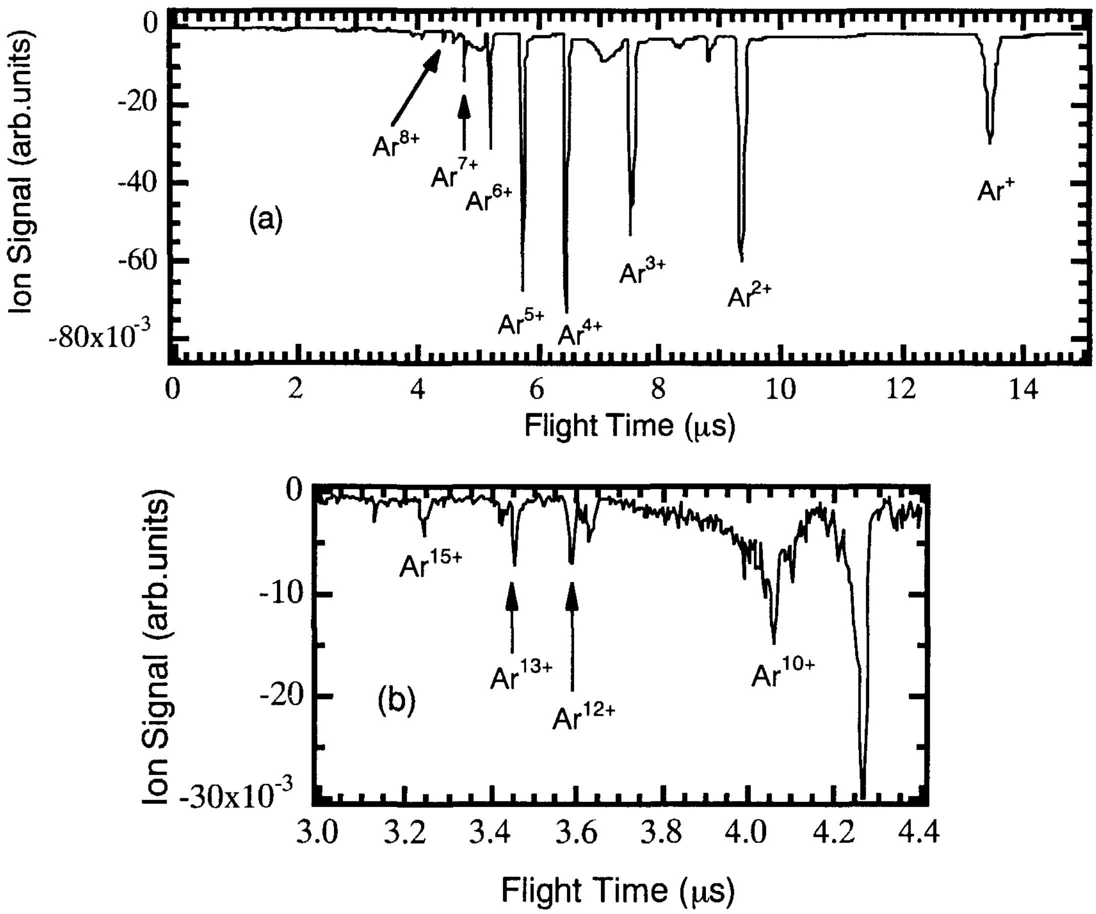

Fig. 2 Typical TOF argon spectra detected by the EMT (a) and the MCP (b), respectively.

3. Experimental Results

A typical TOF spectra of argon at the gas pressure of 1.6×10^{-6} Torr and 4.0×10^{-7} Torr are shown in figure 2(a) and (b), respectively. In these figures, the first eight ion charge states are clearly observed and highly-charged argon ions up to Ar^{15+} were also detected.

The experimental ion yield for Ar^{9+} is presented in figure 3. Each data point typically corresponds to 4000 laser shots. In general, ionization under a strong field is divided into two regimes, multiphoton and tunneling ionization. These two regimes are usually distinguished by the Keldysh parameter $\gamma = (I_P/2U_P)^{0.5}$, where I_P is the atom (or ion) ionization potential and U_P is the ponderomotive potential, given by $U_P = e^2E^2/4m\omega^2$ (e and m are the electron's charge and mass, and E and ω are the field's strength and frequency) [12]. The multiphoton regime corresponds to γ>>1, and the tunneling regime to γ<<1. For example, γ is corresponded to 0.25 for Ar^{8+} at appearance intensity of 2×10^{16} W/cm^2. Therefore, ionizations over Ar^{8+} are thought to be within the tunneling regime. The ion yields of various argon charge states calculated by ADK theory as a function of the peak intensity for pulse duration of 20 fs are also indicated in this figure. Ar^{9+} can be saturated at a peak intensity of 2×10^{18} W/cm^2 defined as $\int W^{ADK}dt = 1$, where W^{ADK} is the ionization rate of ADK theory. From this comparison, we can determine the laser intensity over 10^{18} W/cm^2. From the energy scaling of the laser pulse, the maximum peak intensity corresponds to $\sim2\times10^{19}$ W/cm^2 at the laser pulse energy of 100 mJ.

4. Summary

We have produced the highly charged ions of argon by optical field ionization in the relativistic regime. Inner shell electrons (n = 2) are removed in which ion charge states as high as Ar^{15+} have been observed. We have determined the focused peak intensity of the laser pulse by comparing the measured ion production curve for Ar^{9+} with the ADK theory. The results of the measurements indicate that the maximum peak intensity is reached to $\sim2\times10^{19}$ W/cm^2.

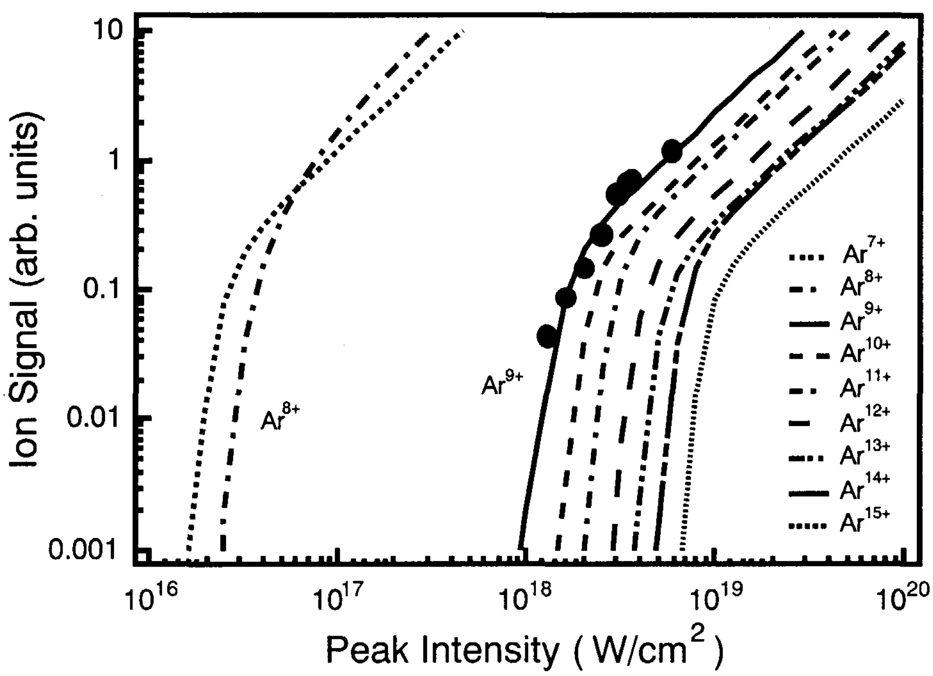

Fig. 3 Argon ion production rate as a function of peak intensity using a Ti: sapphire laser. Theoretical curves are from ADK theory.

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