Plan of multiple ionization experiment with ultra fast TW-laser in RIKEN

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A plan to produce highly charged ions with ultra-fast Tera Watt laser in RIKEN is described. In the first stage of the experiment, the momentum distribution of HCI with the fs TW laser will be studied with COLTRIMS technique.

Multiple ionization processes induced by a strong electric field have recently been studied with fs TW lasers.[1–11] This process is very useful for, *e.g.*, a production of slow highly charged ions (HCIs) of unstable nuclei because one of the peculiar aspects of the TW-laser induced HCI is literally its short production time (several 100 fs). Actually a Radio Isotope Beam Factory (RIBF) is under construction at RIKEN, where various RI beams of several 100 MeV/u are available with projectile fragmentation technique. In this direction we are currently developing a highly efficient RI ion guide system to decelerate the above RI beam down to a few eV.[12] The singly charged slow RI ions thus produced will be introduced into an electro-magnetic trap after multiple ionization with the TW laser for high precision q/m measurements.

The HCI production mechanisms themselves are not necessarily well understood. The basic mechanism of HCI formation under strong laser field is thought to be a sequential tunneling of bound electrons. However, surprisingly large yields of HCI's have been observed even when a laser field is not strong enough to produce HCI's by sequential electron tunneling.[1–5] Assuming sequential ionization of electrons, predicted yields of HCI are lower by many orders of magnitude. This observation of large yields of HCIs has been the subject of controversial debate. Three dynamics mechanisms have been proposed to explain the enhanced yields: (1) Electrons of a core ion are shaken off into continuum when one electron is rapidly removed by a laser field.[2] (2) The laser field accelerates the ionized electrons, which rescatter and further ionize the core ion.[6–8] (3) Collective multielectron tunneling occurs.[9] Recently, as for doubly and triply ionization of rare gas atom around 1 PW/cm^2, momentum distributions of produced ions were measured using Cold Target Recoil Ion Momentum Spectroscopy (COLTRIMS) technique.[10,11] Distinct peak are observed around non-zero momentum in their momentum spectra along the light polarization. Their results and a theoretical calculation[13] show that the rescattering process cited above, *i.e.*, the ionization of the core ions with the accelerated free electrons is responsible for the enhancement.

Table 1. Specifications of our fs TW laser.

Wave length:	775 nm
Energy:	250 mJ
Pulse width:	200 fs(FWHM)
Beam diameter:	40 mm
Repetition rate:	10 Hz
Energy stability:	±5%

A fs TW laser is prepared to study the production mechanism of HCIs under strong laser field (about 100 PW/cm^2). Table 1 shows the specification of the laser. Our fs TW laser is based on Chirped Pulse Amplification (CPA) method.[14] A mode-locked fiber laser and Regenerated Amplifier (RGA) are assembled in a temperature controlled case (modified CPA2001:Clark-MXR Inc.). Chirped pulse light (around 775 nm) from CPA2001 is introduced to a 4-path post amplifier. The post amplifier consists of a Ti:S crystal, a 2J green YAG laser system and eight 780 nm mirrors. The laser energy per pulse is amplified by about 300 times using the post amplifier. After post amplification, chirped pulse light is compressed to about 200 fs using double grating pulse compressor system. A half of the intensity is lost in the pulse compressor system. Figure 1 is a photograph of our laser system.

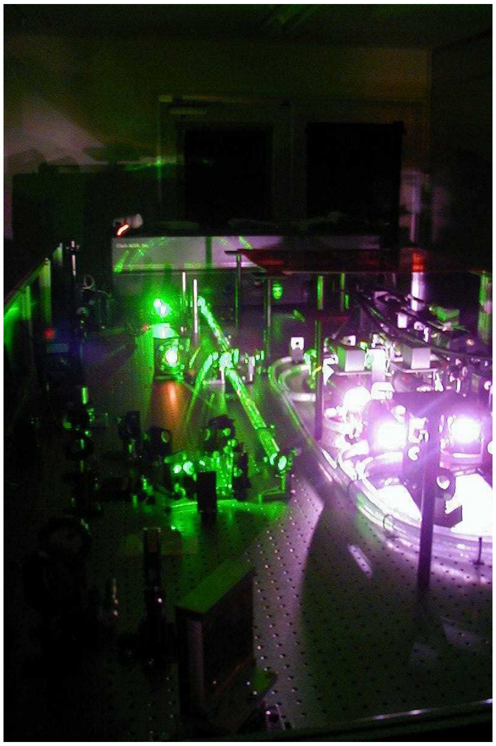

Fig. 1. Photograph of our laser system.

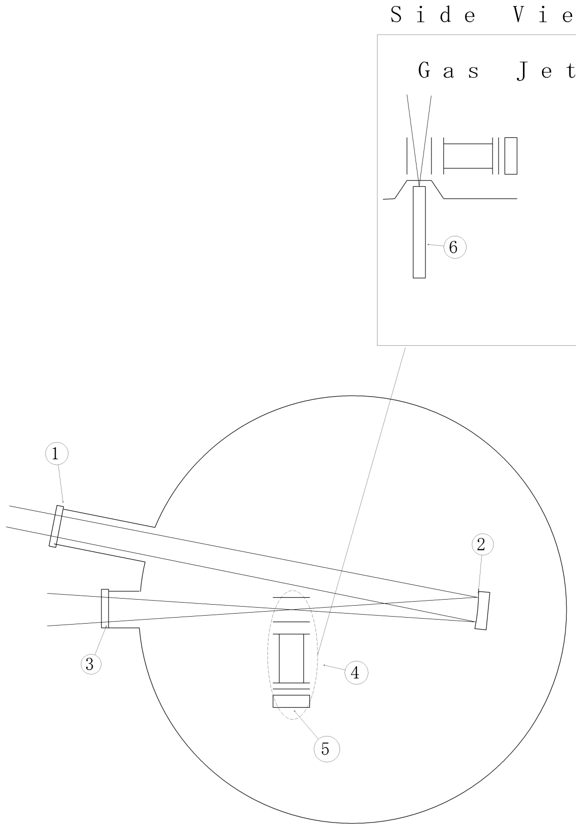

Fig. 2. Schematic drawing of a plan of our experimental setup (top view). 1: entrance window, 2: parabolic mirror, 3: exit window, 4: TOF analyzer, 5: position sensitive ion detector, and 6: gas reservoir.

Figure 2 shows a schematic drawing of our experimental setup. To obtain enough power density to produce HCIs, the laser beam with 40 mm diameter will be introduced into a vacuum chamber via a fused-silica glass window, and then will be focused by an off-axis parabolic mirror (focal length is 300 mm) down to about 40 micron in diameter.

The peak power density at the target position will be about 100 PW/cm^2. A Coulomb-barrier suppression model, [15] which is a Classical Over-Barrier model in a DC electric field, predicts that our power density is strong enough to produce, *e.g.*, Ne^{6+}, Ar^{8+}, and Xe^{11+} ions as shown in Fig. 3. Production of higher charge state will be expected due to ionization of the core ion by rescattering of oscillating free electrons which are ionized by tunneling ionization. The maximum energy of oscillating free electron, K_e, in a laser field is classically estimated by

$$K_e = 8 \times U_p \qquad (1)$$

$$U_p(\mathrm{eV}) = (9.33 \times 10^{-14}) \times I(\mathrm{W/cm^2}) \times \lambda^2(\mu\mathrm{m}) \qquad (2)$$

(the formula of U_p is in Ref. 15) where U_p is a ponderomotive potential, I is a power density of laser, λ is a wavelength of laser light. Because this maximum energy is large enough to ionize inner shell electrons of core ions, inner shell vacancies in the core ions can be produced. Auger transitions are expected to play an additional role to further enhance multiple ionization.

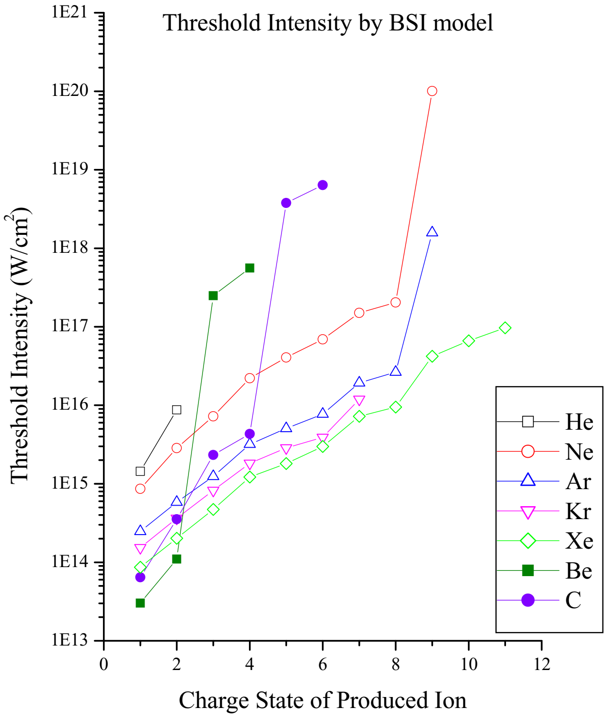

Fig. 3. Threshold power density of ion production for each charge state by Coulomb-barrier suppression model.[15]

In the first stage of the experiment, multiple ionization mechanisms at relatively high laser field will be studied using COLTRIMS technique. Our experimental equipments are under construction. The laser light will be crossed with a gas jet target at the focus point as Fig. 2. The jet will be formed by expanding gases from a temperature controlled gas nozzle (LN$_2$ temperature or higher) and by collimating with a skimmer. The mean energy of recoil ions, K_i, is roughly estimated using a ponderomotive potential U_p as follows:

$$K_i = U_p \times q^2 \times m_e/M_{\mathrm{ion}} \qquad (3)$$

where q is the charge state of the recoil ion, m_e is the mass of electron, M_{ion} is the mass of the recoil ion. At our peak power density, the mean energy of recoil ion along the light polarization is estimated to be about 1.5 eV for Xe^{8+}, *i.e.*, the targe gas at LN$_2$ temperature is low enough, which is quite different from the recoil ion spectroscopy in fast ion-atom collisions. A space focusing Time-of-Flight (TOF) analyzer will be used. Because various low charge state ions will be produced from residual gases, a mass gate using a high voltage pulse will be used after a drift tube of the TOF analyzer to exclusively select highly charged ions. The momentum along the extraction direction will be determined with the TOF and that perpendicular will be determined with the position on the position sensitive recoil ion detector.

A 1% laser light separated with a 1% penetrating flat mirror will be monitored with a power meter to measure long time stability and also with a photo diode to measure relative intensity of each pulse. A CAMAC based data acquisition system will be used to measure recoil ion momentum and output signals from the photo diode in the first experimental stage.

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