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Development of an apparatus for femtosecond laser-assisted (*e*,2*e*) experiments

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Abstract. We developed an electron scattering apparatus equipped with dual angle-resolved time-of-flight analyzers designed for laser-assisted (e,2e) experiments, with which atomic and molecular orbitals influenced by intense laser fields can be investigated.

1 Introduction

Through repetitive coincidence detection of a scattered electron and an ejected electron generated by a single event of electron impact ionization, which is called (*e*,2*e*) experiments, we can perform kinematically complete measurements to obtain the triply differential cross section of the electron impact ionization process. Because the binding energy of the ejected electron can be determined from the sum of the kinetic energies of the scattered and ejected electrons, we can specify the orbital occupied by the ejected electron in the initial state of the target. Therefore, by the (*e*,2*e*) experiments, we are able to investigate orbital-selective processes of atoms and molecules [1] and their ionization processes induced by the non-dipole interaction between the projectile and the target [2].

When electron impact ionization occurs under the presence of a laser field, the sum of the kinetic energies of the scattered electron and the ejected electron changes by multiples of the photon energy, $n\hbar\omega$, with n being an integer. This process is called laser-assisted electron impact ionization (LAEII) [3]. If coincidence detection of the scattered and ejected electrons are conducted for LAEII processes, we can also specify the orbital occupied by the ejected electron, and can investigate characteristics of the orbital that could be influenced by the laser field. Considering that a wide variety of atomic and molecular dynamics induced by ultrashort intense laser fields have been explained well by the single-active-electron model, the investigation of atomic and molecular orbitals in intense laser fields by laser-assisted (*e*,2*e*) measurements will give us fundamental understanding of electron correlations within atoms and molecules in intense laser fields. In 1988, Joachain *et al.* [4] theoretically investigated LAEII of a hydrogen atom influenced by a strong laser field, and found that the triply differential cross section of the LAEII process increases significantly by the laser-atom interaction. In 2005, Höhr *et al*. [5] reported the results of their LAEII measurements of He in a nanosecond laser field (λ = 1064 nm, Δt = 7 ns, I = 4

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$\times 10^{12}$ W/cm^2) by the coincidence detection of the ejected electron and the created ion, and showed that the triply differential cross section increases by 10% under the presence of the laser filed, which can be regarded as the phenomenon originating from the interaction between the target and the laser field.

In the present study, in order to investigate how atomic and molecular orbitals are influenced by intense laser fields, we developed an apparatus for measurements of LAEII processes induced by femtosecond intense laser pulses. In order to achieve sufficiently high energy resolution, we employed coincidence detection of the scattered electron and the ejected electron in LAEII processes. From the (e,2e) experiments of Ar atoms without laser fields, the energy resolution of the present apparatus was found to be about 1 eV, with which we can specify orbitals from which an electron is ejected as well as photon numbers involved in LAEII processes.

2 Apparatus

Figure 1 shows a schematic of the apparatus. A pulsed electron beam with the duration of 20 ps is generated by a photocathode-type pulsed electron gun, and collides with a sample gas at the scattering point. Simultaneously, a femtosecond intense laser beam (λ = 800 nm, Δt = 50 fs, 1 mJ) is introduced into the scattering point. When the electron impact ionization is induced by an electron pulse whose kinetic energy is as high as 1 keV, most of the projectile electrons are scattered forward within the small angle range with large kinetic energies while the ejected electrons are emitted to the wide angle range. Therefore, we developed two different-type angle-resolved time-of-flight analyzers, i.e., one analyzer designed for detecting the scattered electrons having a small acceptance angle of 8.0 degrees with the energy resolution as high as 1 eV even for high kinetic-energy electrons around 1 keV and the other analyzer designed for detecting the ejected electrons having the large acceptance angle of 120.0 degrees. By the two angle-resolved time-of-flight analyzers integrated into the apparatus as shown in Fig. 1, 90% of the scattered electrons and 20% of the ejected electrons can be collected when the kinetic energy of the incident electron is 1 keV. The two analyzers are equipped with a position-sensitive detector with delay-line anodes, so that the emission angle and the kinetic energy of the electrons can be determined from the detected position and the time-of-flight of the electrons. By synchronizing two position-sensitive detectors, coincidence measurements of the scattered electron and the ejected electron can be made.

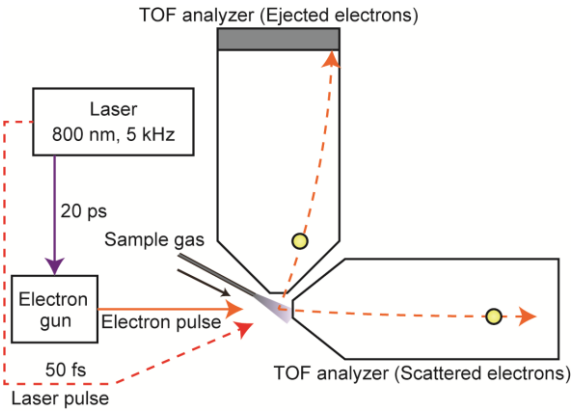

Fig. 1. Schematic of the apparatus for the measurements of LAEII processes induced by femtosecond intense laser pulses.

3 Results and discussion

In order to confirm the performance of the apparatus, we conducted (*e*,2*e*) experiments of Ar atoms without laser fields. Figure 2 shows a correlation map between the energy of the scattered electrons, E_{sc}, and that of the ejected electrons, E_{ej}, which were detected in coincidence. The sum of the energies of the scattered electrons and the ejected electrons in the field-free electron impact ionization process should fulfil the energy conservation law,

$$E_{sc} + E_{ej} = E_i - U_{IP}, \quad (1)$$

where E_i is the kinetic energy of the incident electron and U_{IP} is the ionization potential corresponding to the respective ionization processes. Consequently, true coincidence events should form a straight line with the slope of −1 in the correlation map. As shown in Fig. 2, two straight lines are seen clearly in the recorded correlation map, and the ionization potentials evaluated from the strong line and the weak line are 15.6±0.5 eV and 28.8±0.5 eV, respectively, which are consistent with the literature values of the ionization potentials for the 3p-ejection (15.8 eV) and the 3s-ejection (29.2 eV), respectively.

The energy resolution of the sum of the energies of the two electrons is determined to be about 1 eV (FWHM), which is sufficiently high for determining the ionization potentials as well as for resolving the energy separation of 1.6 eV, corresponding to one-photon energy between the adjacent LAEII signals induced by near-IR ($\lambda \sim 800$ nm) laser pulses. The count rate of the coincidence events for the 3p-ejection process is around 1 count/s. Because the triply differential cross section of the LAEII processes with $n = \pm 1$ is expected to be only 0.1~1% of that of the field-free electron impact ionization process, the count rate of the coincidence events for the LAEII processes is estimated to be about 1 count/hour.

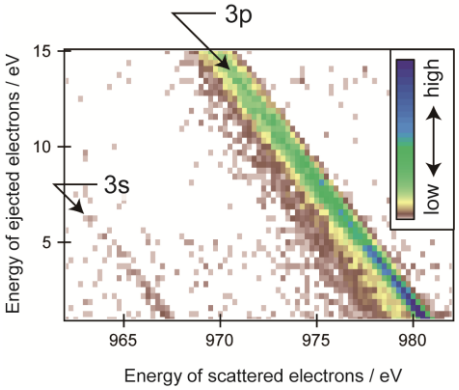

Fig. 2. Energy correlation map between the scattered electrons and the ejected electrons generated through the electron impact ionization of Ar.

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