Nonlinear optical effect in the soft x-ray region by two-photon ionization of He^+

Kenichi Ishikawa and Katsumi Midorikawa

Laser Technology Laboratory, RIKEN (The Institute of Physical and Chemical Research), Hirosawa 2-1, Wako-shi, Saitama 351-0198, Japan

+81-48-467-9501, +81-48-462-4682, ishiken@postman.riken.go.jp

Abstract: We numerically show that the two-photon ionization of He^+ by 27th harmonic pulses of a Ti:Sapphire laser is suitable for the observation of a nonlinear optical effect in the soft x-ray region.

OCIS codes: (190.4180)Multiphoton processes; (320.7110)Ultrafast nonlinear optics

The recent progress in the high-order harmonic generation technique has enabled the production of high-power soft x-ray pulses. The generation of 30fs-27th-harmonic pulses ($\lambda = 29.6\,\mathrm{nm}$) of a Ti:Sapphire laser with an output energy as high as 500 nJ has recently been reported [1]. When we focus such a pulse to an area of $10\,\mu\mathrm{m}^2$, its average intensity reaches $10^{14}\,\mathrm{W/cm}^2$. With this intensity, the first observation of a nonlinear optical effect in the soft x-ray region may be realizable.

In this study, we perform numerical experiments of two-photon ionization of He^+. Why He^+? Because He^+ is easy to prepare from He, e.g., by optical field ionization. Its $1s - 2p$ transition energy (40.8 eV) is close to the photon energy (41.85 eV) of the 27th harmonics of a Ti:Sapphire laser. Moreover, the exact solution can be given for this simple system. Why numerics? Because the analytical cross section formula may break down for high intensity and ultrashort pulse duration. Our results show that this process is an attractive candidate for the observation of a nonlinear optical effect.

We solve the time-dependent Schrödinger equation in length gauge using the Peaceman-Rachford method [2], and evaluate the ionization yield as the number of electrons absorbed by the mask function at the outer radial boundary.

Figure 1 shows the yield of He^{2+} obtained by a gaussian 27th-harmonic pulse with a duration (FWHM) of 30 fs as a function of peak intensity $I_{\max}$. The analytically obtained cross section σ is $2.9 \times 10^{-52}\,\mathrm{cm}^4\mathrm{s}$. From this figure, the ionization probability at $I_{\max} > 10^{13}\,\mathrm{W/cm}^2$ is sufficiently high to be observed experimentally. Although saturation is seen at $I_{\max} > 10^{13}\,\mathrm{W/cm}^2$, the yield still has a nearly quadratic dependence on $I_{\max}$ there. This is one of the desirable properties for applications such as pulse duration measurements.

We check the linearity in pulse duration t_0 in Fig. 2. The linear relation holds at $t_0 > 5\,\mathrm{fs}$, for which the two-

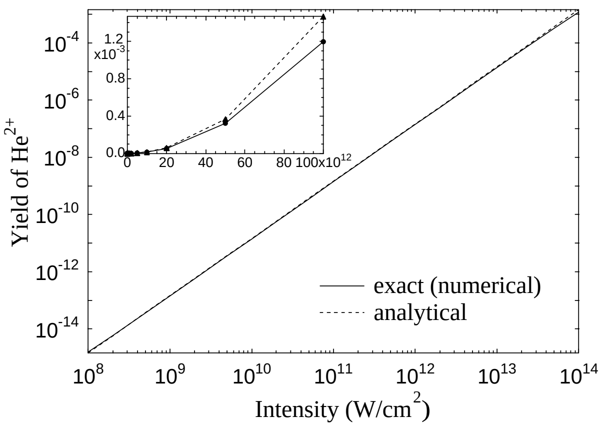

Fig. 1: Yield of He^{2+} vs. peak intensity of a gaussian 30fs-27th-harmonic pulse. Solid line: numerical results. Dotted line: analytical results $\int_{-\infty}^{\infty} \sigma I(t)^2 dt$. Inset: the same in a linear scale.

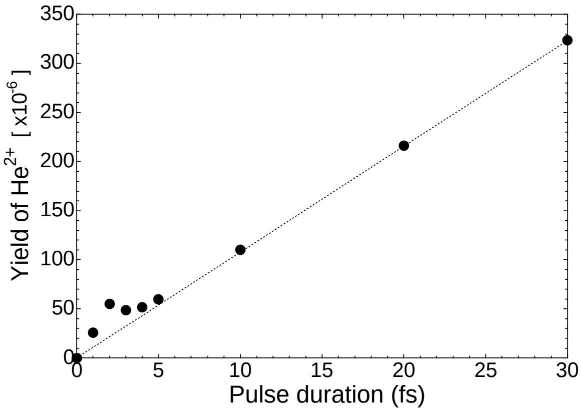

Fig. 2: Yield of He^{2+} vs. pulse duration of a gaussian 27th-harmonic pulse with a peak intensity of 5×10^{13} W/cm^2.

photon ionization of He^+ by the 27HG can be applied for autocorrelation experiments. On the other hand, the linearity breaks down for shorter pulses. As a consequence, the He^{2+} yield attained by two consecutive pulses is NOT twice that by a single pulse as can be seen in Fig. 3 (solid line). The linear dependence is, however, recovered by the use of more detuned pulses, e.g., the 23HG (Fig. 3, dashed line). We have confirmed that the dependence on intensity is quadratic even for such ultrashort pulses.

In conclusion, by numerical simulations we have shown that the two-photon ionization of He^+ is suitable for the realization of a nonlinear optical effect in the soft x-ray region, with its high cross section, quadratic dependence on intensity, and linearity in pulse duration.

References

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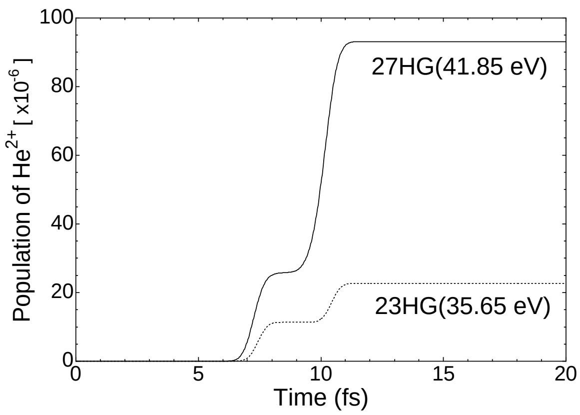

Fig. 3: Temporal evolution of the population of He^{2+} by two consecutive 1fs-27th-harmonic pulses (solid line) and 1fs-23rd-harmonic pulses (dotted line), respectively. The peak intensity of each pulse is 5×10^{13} W/cm^2, and the interval between the two pulse peaks is 3 fs.