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Free Electrons Generation in the Interaction of Intense Laser Pulses with Atomic Clusters

M. Rusek and A. Orłowski

Institute of Physics, Polish Academy of Sciences
al. Lotników 32/46, 02-668 Warsaw, Poland

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Interaction of argon clusters with intense laser pulses is studied theoretically. Free electrons energy distribution is studied. Differences between infrared and vacuum ultraviolet frequency regimes are pointed out. Clear physical interpretation of the obtained results is given.

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1. Introduction

The production of electrons from individual atoms through multi-photon and tunnel ionization has been thoroughly studied in the recent years. The experiments on laser interactions with atomic clusters have suggested that the laser–cluster interaction is more energetic than that of isolated atoms. Efficient generation of highly-charged atomic ions [1–5], generation of electrons and ions with MeV kinetic energies [4, 6–8], and emission of intense X-rays [2, 9, 10] were observed.

These experiments were performed mainly in the infrared or optical laser frequency regime. Only recently reports on the interaction of clusters with short-wavelength pulses in the vacuum ultraviolet frequency range appeared [11, 12]. The short-wavelength photons with energy sufficient to ionize isolated xenon and almost sufficient to ionize argon atoms were generated by a free-electron laser. The cluster explosion and ionization mechanisms in this frequency regime [11–13] turn out to be very different from that known from the infrared and optical pulses [14, 15].

In this paper we further extend the theoretical results obtained in our previous papers [13, 15] and investigate the kinetic energy distribution of the free electrons generated in the process of laser interaction with rare-gas atomic clusters. A time-dependent Thomas–Fermi model allows us to study both the infrared and short-wavelength frequency cases in the same unified way.

We assume that the oscillations of the electron cloud in a rare-gas atomic cluster can be viewed as a motion of a fluid characterized by a density, and a velocity field obeying the standard conservation equations for number of particles and momentum [14, 15]. These hydrodynamic equations for the electron density ρ should be supplemented by the Newton equations of motion for the positions of the nuclei [14, 15]. The interaction with the laser pulse is treated within the dipole approximation [14, 15]. The linearly polarized wave of a pulse used in the simulations is assumed to have a field envelope proportional to sine squared [14, 15].

The initial structure of the 55 and 147 atom argon clusters was chosen to be that of a closed-shell icosahedron with an atom spacing of 3.7 Å [14]. The initial value of the electron density $\rho(\boldsymbol{r}, t_0)$ is obtained by looking for the minimum of the Thomas–Fermi energy functional [14].

The atoms of the cluster have initially no kinetic energy and are subject to an oscillating electric laser field at the peak intensity of 10^{14} W/cm^2, wavelength 98 nm (or $\tau_0 = 13.527$ a.u.), and temporal full width at half maximum of 50 fs. These parameters were used in the experiments [12] and in our previous theoretical paper [13].

2. Results and discussion

In Fig. 1 we present the kinetic energy spectrum of the free electrons emitted in the explosion process of 55 and 147 atom argon clusters illuminated by a short--wavelength laser pulse at 98 nm. It is seen from inspection of this figure that the released electrons are not very energetic: their kinetic energies are well below 100 eV (this should be contrasted with an optical case, where multi keV energies were measured [6]). The mean kinetic energy of emitted electrons seems to increase with cluster size. In addition in Fig. 2 we show the same spectrum but plotted in log-linear scale. It is seen that the spectrum is a clear exponential, i.e., $P(E) \propto \exp(-E/E_0)$.

The energy of an electron emitted in an n-photon ionization event is given by

$$E_n = n\hbar\omega_0 - I_{\mathrm{p}}, \tag{1}$$

where ω_0 is the laser frequency and I_{p} denotes the ionization potential of an atom in the investigated cluster. At 98 nm laser wavelength the energy of a single photon is $\hbar\omega_0 = 12.7$ eV. At least two free-electron laser photons are needed to ionize an argon atom, because the ionization potential is $I_{\mathrm{p}} = 15.76$ eV. The first

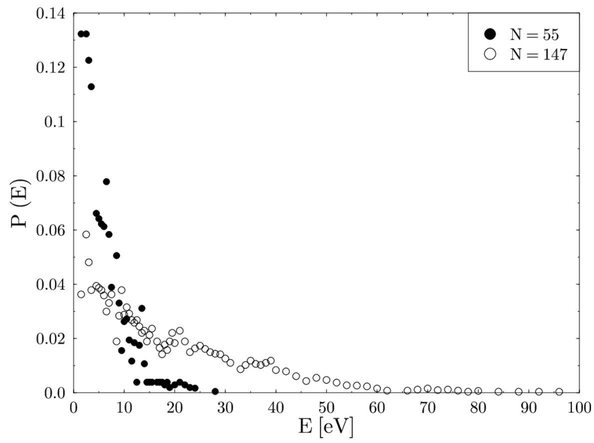

Fig. 1. Distribution of the final kinetic energies of free electrons produced in the explosion of 55 and 147 atom clusters illuminated by short-wavelength pulse at 98 nm.

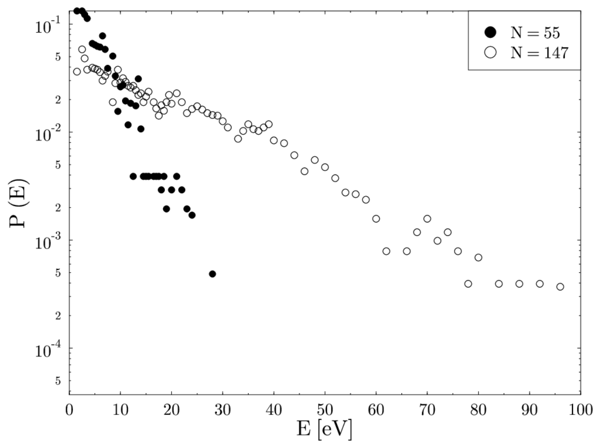

Fig. 2. The same as in Fig. 1 but plotted in log-linear scale.

electrons emitted should have kinetic energy around $E_2 = 9.64$ eV. However this and following energy maxima are not visible in Figs. 1 and 2. We conclude therefore that the electrons released from the cluster do not remember their original kinetic energy. First, their kinetic energy is used to heat the cluster plasma. This occurs during collisions between electrons released from individual atoms but remaining bounded by the cluster as a whole (by cluster ions). This *inverse bremsstrahlung* process is a very effective way of the laser energy deposition in the cluster [12, 13]. Next, the quasi-free electrons inside the cluster gain enough energy to overcome the Coulomb potential barrier. Finally, they leave the cluster by a kind of thermionic electronic emission. This thermionic emission mechanism was suggested in the experimental paper [11].

Let us now investigate the free electrons behavior in the infrared frequencies regime. The pulse used in the simulations had an intensity $I = 1.4 \times 10^{15}$ W/cm^2, wavelength 800 nm, and a temporal full width at half maximum 106.67 fs. This is a typical infrared frequency pulse which was also used in our previous theoretical paper [15]. In this case the photon energy is $\hbar\omega_0 = 1.55$ eV.

In Fig. 3 we present the energy distribution of free electrons released from a 55 atoms cluster due to the cluster interaction with the above described infrared pulse. The energy maxima corresponding to multi-photon processes are not directly visible, presumably due to the energy scale and coarse graining introduced

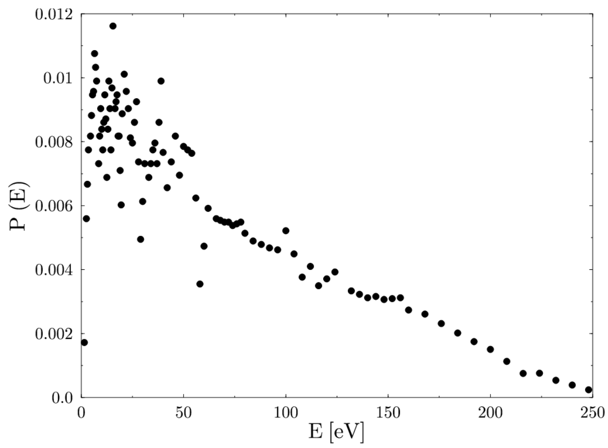

Fig. 3. Distribution of the final kinetic energies of free electrons produced in the explosion of 55 atom cluster illuminated by infrared pulse at 800 nm.

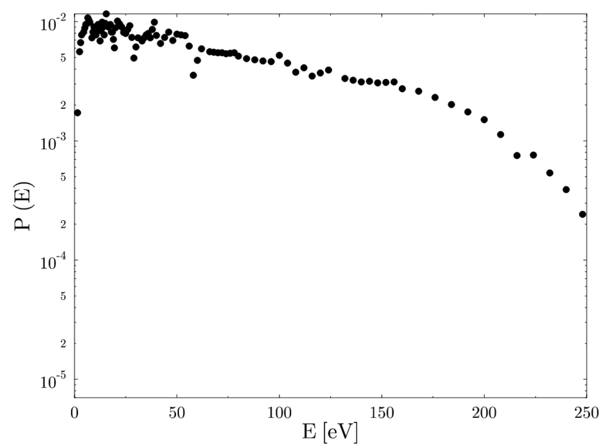

Fig. 4. The same as in Fig. 3 but plotted in log-linear scale.

by the distribution calculations. Nevertheless, we can see some strong oscillations, which suggest that these maxima are, in principle, present in the investigated case.

In the experimental paper [6] two distinct lobes (corresponding to warm and hot electrons, respectively) are reported for xenon atoms illuminated by a ten times stronger pulse than studied in our paper. Our distribution resembles the warm electron part of the corresponding plot in [6]. The lack of any pronounced hot electron part in our calculations could be due to the not sufficient size of our cluster. This seems to be in agreement with the remark made in [6] that this hot part shows up only for large enough clusters.

In Fig. 4 we have the same plot in the log-linear scale. Therefore we can easily see that in contrast to the previous short-wavelength case the energy distribution dies out much slower than exponentially. A linear fall-off seems to be a good approximation to the observed behavior.

3. Conclusion

In summary, spectra of free electrons released in the explosion process of argon clusters illuminated by a short-wavelength laser pulse were studied theoretically. Analysis of these spectra reveals that in the explosion process the cluster undergoes several different phases. First, *inner ionization* of cluster atoms leads to formation of the plasma. In the beginning it consists of one quasi-free electron per atom. These electrons are released from individual atoms but remain bounded by the cluster as a whole. The laser energy deposition is mainly controlled by the *inverse bremsstrahlung* process. These quasi-free electrons inside the cluster eventually gain enough energy to overcome the Coulomb potential barrier, so they can leave the cluster by a kind of thermionic electronic emission. In the realm of the optical frequencies the emitted electrons energy spectrum is different. Instead of an exponential behavior we observe a linear fall-off. This suggests a different explosion mechanism prevailing in this case. For a small cluster considered, all the electrons are removed from the cluster by a laser pulse and the Coulomb explosion of the positively charged ions follows.

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