Volume 9, Number 5
1009-1963/2000/09(05)/0351-02
CHINESE PHYSICS
May, 2000
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ENERGETIC ABOVE-THRESHOLD IONIZATION SPECTRA OF H-ATOM IN INTENSE LASER FIELDS*

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(Received 9 November 1999; revised manuscript received 29 December 1999)

The above-threshold ionization (ATI) spectra of H-atom in intense laser fields (laser intensity I is up to $10^{18}\mathrm{W/cm^2}$) are calculated. It is found that the kinetic energy of the ejected electron at the location of the peak of the ATI spectra is about equal to the corresponding ponderomotive potential of the applied laser fields. This result is consistent with that obtained by Wilks *et al.* and fits the experimental results of the super thermal electron. A possible new mechanism of the super thermal electron generation is proposed.

PACC: 3280; 5240

Recent observations of MeV electrons escaping from plasma have been made on high intensity pico-second interactions with solid targets and a pulsed gas jet. The fast ignition concept[1], relevant to the inertial confinement fusion (ICF) studies, enhances the interest to investigate the generation of the super thermal electrons (STE) by this interaction. How to understand the mechanism of the STE generation has attracted wide attention. Wilks *et al.* has performed the particle-in-cell (PIC)simulations of the interaction of an intense pico-second laser pulse with a solid target. The PIC simulations show that the distribution of the super thermal electron is described by a Boltzmann distribution $f(W) = \mathrm{d}N/\mathrm{d}W \approx \exp(-W/k_{\mathrm{B}}T_h)$, where k is Boltzmann constant, W is the energy of STE, N is the number of STE and T_h is defined as the temperature of the super thermal electron. Wilks *et al.* found also that kT_h is about equal to the quiver energy of the electron W_{osc}.[2]

$$W_{\mathrm{osc}} = (\gamma_{\mathrm{osc}} - 1)mc^2,$$
$$\gamma_{\mathrm{osc}} = \frac{1}{\sqrt{1 - \dfrac{v^2}{c^2}}} = \sqrt{1 + a^2}. \qquad (1)$$

In Eq.(1), a characteristic parameter, a is introduced.

$$a = \frac{p_{\mathrm{osc}}}{mc} = \frac{eE}{mc\omega} = 8.53 \times 10^{-10}\sqrt{I\lambda^2}, \qquad (2)$$

where e is the electron charge, c the light speed, m the mass of electron, p_{osc} the quiver momentum of electron, E the magnitude of the laser field at focus, λ the laser wave length in microns, I the laser intensity in $\mathrm{W/cm^2}$.The above PIC simulation shows that the interaction between the applied laser and the plasma generates the STE.

In the paper we report that the STE can be directly generated from the ionization process of atoms in an intense laser field. In order to show the conclusion, let us first calculate ATI spectra of H-atom in an intense laser field.

According to Ref.[3], the transition probability for N-photon ionization per unit time per solid angle by the circularly polarized laser, $\mathrm{d}W_N/\mathrm{d}\Omega$, reads

$$\frac{\mathrm{d}W_N}{\mathrm{d}\Omega} \propto k_{\mathrm{f}}(|E_i| + E_{\mathrm{f}})^2 |\hat{\phi}_i(\boldsymbol{k}_{\mathrm{f}})|^2 \mathrm{J}_N^2(\sqrt{z}\gamma)$$
$$z = \frac{I}{4\omega^3}, \quad \gamma = 2k_{\mathrm{f}}\sin\theta. \qquad (3)$$

Here, I is the laser intensity, ω the laser frequency, E_i the binding energy of H-atom in ground state, E_{f} the kinetic energy of the final state electron, $\boldsymbol{k}_{\mathrm{f}}$ the momentum of the final state electron, θ the angle between the propagation direction of the laser and the momentum $\boldsymbol{k}_{\mathrm{f}}$, $\hat{\phi}_i$ the Fourier transformation of the ground state function of H-atom, $\mathrm{J}_N(x)$ the Bessel function of N order and $k_{\mathrm{f}} = |\boldsymbol{k}_{\mathrm{f}}|$.

In should be pointed out that in order to simplify the numerical calculation we consider neither the final state Coulomb interaction nor the level shift of the atom.[4].

Using Eq.(3), we calculate the ATI spectra of H-atom with four different intensities of the applied laser field with ω=1.55eV : $3.5 \times 10^{15}\mathrm{W/cm^2}$; $3.5\times10^{16}\mathrm{W/cm^2}$; $3.5\times10^{17}\mathrm{W/cm^2}$; $1.8\times10^{18}\mathrm{W/cm^2}$.

According to the calculated results, we find the locations of the peak of the spectra and form Table.1. For the sake of comparison, the ponderomotive potentials of the corresponding intensities are also included in Table.1.

Table 1. Location of the peak of ATI and the ponderomotive potential at four laser intensities.

* Project supported by the National Natural Science Foundation of China (Grant No. 19784001), the National High-Tech ICF Committee of China and the Research Fund for Doctoral Program of Higher Education (Grant No. 98002713).

Intensity /(10^{16}W/cm^2)	Peak location /keV	Ponderomotive potential/keV
0.35	0.25	0.22
3.50	2.18	2.20
35.0	21.8	22.0
180.0	111.4	113.0

We list the calculated ATI spectra with $I = 1.8 \times 10^{18}$W/cm^2 in Fig.1. From Fig.1 we can see that the ATI spectrum has a single peak. From Table 1 we see clearly that the kinetic energy of ionized electron at the peak of the ATI spectra is approximately equal to the ponderomotive potential of the laser field. Qualitatively speaking, this result (the kinetic energy is about equal to the ponderomotive potential) is consistent with that given by Wilks *et al.* and fits the experimental results.[5] It should be pointed out, however, that the two numerical results provide the different explanations to the physical origin of the STE. According to Wilks *et al.*[2] the STE are generated in the processes of laser-plasma interaction. According to this paper the STE, however, are generated (at least a portion of them) in the processes of atom ionization.

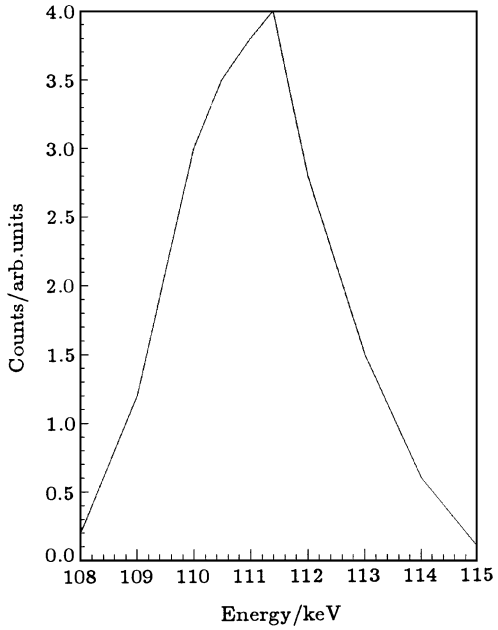


Fig.1. ATI spectra of H-atom (ω=1.52 eV,$I = 1.8 \times 10^{18}$W/cm^2).

Finally, it should be pointed out that Eq.(3) is obtained under the non-relativistic approximation. For $I \sim 10^{18}$W/cm^2, $a \sim 1$ and the non-relativistic approximation works marginally. For $I \gg 10^{18}$W/cm^2, the non-relativistic approximation does not work. Taking the relativistic effects into account is under work.

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