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NONSEQUENCE DOUBLE IONIZATION OF HELIUM AND CORRELATED ELECTRON EMISSION

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In this paper, a quasistatic model is extended to describe the double ionization of Helium in intense linearly polarized field. Our numerical calculations reproduce the excessive double ionization and the photoelectron spectra observed experimentally both quantitatively and qualitatively. Moreover, the correlation between magnitude and direction of momentum in the polarization axis of two emission electrons has been studied.

1. Introduction

The excessive double ionization observed in Helium, experiments,[1−3] draws much attention to the multiple-electron dynamics in the laser-atom interaction. In these experiments, in the regime of very high intensities ($I > 10^{16}\text{W/cm}^2$), the double ionization keeps in good agreement with the sequential single active electron (SAE) models as that in the lower intensities regime ($I < 10^{14}\text{W/cm}^2$). The double ionization yield deviates seriously from the sequential SAE model and shows a great enhancement in a "knee" regime [$(0.8\text{—}3.0) \times 10^{15}\text{W/cm}^2$]. This surprising large yields of the double ionization obviously indicates that the sequential ionization is no longer the dominating process in this regime and the electron-electron correlation has to be taken into account. The physical mechanism behind this nonsequential process is, however, still debatable. Both the "shake-off" model and the "recollision" model are suggested to describe the electron's correlation.[1,3,5,6] However, none of the two nonsequence double ionization (NSDI) mechanisms can completely explain the experimental observations.

In this paper, based on a developed semiclassical model, we study the double ionization of helium in intense linearly polarized field. Our calculations reproduced the excessive double ionization and the photoelectron spectra observed experimentally both quantitatively and qualitively, and we argue that classical collisional trajectories as the main source of the nonsequence double ionization of helium in the "knee" regime. By using this model we also investigate the correlated electron emission of helium by analyzing the classical trajectories of the double ionization process. The correlation between the direction and magnitude of the momentum of two emission electrons is found in double ionization of helium, and the maximum of the sum and difference momentum parallel to polarization axis is estimated.

2. Model

Firstly, we briefly present the semiclassical rescattering model adopted in our calculations. The ionization of the first electron from bound state to the continues state is treated by the tunnelling ionization theory generalized by Delone *et al.*[7] The subsequent evolution of the ionized electron and the bound electron in the combined Coulomb potential and the laser fields is described by a classical Newtonian equation. To emulate the evolution of the electron, a set of trajectories is launched with initial conditions taken into from the wave function of the tunnelling electron.

The evolution of the two electrons after the first electron tunnelled are described by the classical equations (in atomic unit):

$$\frac{d^2\mathbf{r}_i}{dt^2} = -\nabla(V_n^i + V_{ee}) - \mathbf{F}(t)\,, \qquad i = 1, 2\,. \tag{1}$$

Here $\mathbf{F}(t) = F\cos(\omega t)\vec{e}_z$ is the laser field. The indices $i = 1$ and 2 refer to the tunnel ionized and bound electron respectively. The potentials are

$$V_n^i = -\frac{2}{|\mathbf{r}_i|}\,, \qquad V_{ee} = \frac{1}{|\mathbf{r}_1 - \mathbf{r}_2|}\,.$$

The initial condition of the tunnelled electron, under the SAE approximation of He$^+$, is determined by a equation including the effective potential given in Ref. 8 and a generalized tunnelling formula developed by Delone *et al.*[7] In parabolic coordinates, the Schrödinger equation for a hydrogen-like atom in a uniform field ϵ is written (in atomic unit),

$$\frac{d^2\phi}{d\eta^2} + \left(\frac{I_{p1}}{2} + \frac{1}{2\eta} + \frac{1}{4\eta^2} + \frac{1}{4}\epsilon\eta\right)\phi = 0\,, \tag{2}$$

in which $I_{p1} = -0.9$ *a.u.* is the negative ionization potential of the outer electron.

The evolution of the outer electron is traced by launching a set of trajectories with different initial parameters t_0 and v_{1x0}, where v_{1x0} is the initial velocity perpendicular to the polarization of the electric field. The initial position of the electron born at time t_0 is given by $x_{10} = y_{10} = 0$, $z_{10} = -\eta_0/2$ from the Eq. (2). The initial velocity is set to be $v_{1y0} = v_{1z0} = 0$, $v_{1x0} = v_{10}$. Thus, the weight of each trajectory is evaluated by[7]

$$w(t_0, v_{10}) = w(0)w(1)\,, \tag{3}$$

$$w(1) = \frac{\sqrt{2I_{p1}}v_{10}}{\epsilon\pi}\exp(-\sqrt{2I_{p1}}v_{10}^2/\epsilon)\,, \tag{4}$$

and where $w(0)$ is the tunnelling rate in the quasistatic approximation.[9]

The initial state of the bounded electron is described by assuming that the electron is in the ground state of He$^+$ with energy $E_2 = -2.0$ *a.u.* and its initial distribution is microcanonical distribution.[10]

3. Result and Discussion

In our calculation, the Eq. (1) are solved in a time interval between t_0 and $15T$ by employing the standard Runge-Kuta algorithm. The wavelength is $\lambda = 780\ nm$, which is so chosen to match the experiment.[2,11] The distribution for the ionization electron can be obtained by making statistics on an ensemble of classical trajectories weighed by (3). The results have been tested for numerical convergence by increasing the number of trajectories.

Figure 1 shows the double ionization yields of helium calculated by our model at 13 different intensities in the range $4 \times 10^{14} - 4 \times 10^{15}\ W/cm^2$. The inset in Fig. 3 shows the double ionization rate calculated by our model normalized to the ADK tunneling rate of He versus the intensity. Our result is in good agreement with the data in the knee regime observed in experiments:[2] $\mathrm{He}^{2+}/\mathrm{He}^{+}$ ratio in the knee regime is nearly around 0.002.

From our calculations, we also obtain the photoelectron spectra (PES). Figure 2 shows the total photoelectron energy distribution at $1 \times 10^{15}\ W/cm^2$ and $1.6 \times 10^{15}\ W/cm^2$ (both of them are in the knee regime) calculated from our model. On can see that, in absolute units, an increasing laser intensity results in the increase of higher energy photoelectrons. But if one scales the energy units by the pondermotive energy $U_p = e^2F^2/4m_e\omega^2$, of electron, one will find that the PES for both intensities will show similar shape: The spectrum exhibits a sharply decreasing slope (region **I**, 0–$2U_p$) followed an extended plateau up to $8U_p$ or more (region **II**). This spectrum structure is much close to experimental observations in this regime.[2]

Figure 3 shows the momentum correlation between the two emission electrons in the double ionization of the present calculations. The horizontal axis shows the momentum component of the first electron in the direction of polarization (P_{1z}) and the vertical axis the same momentum component of the second electron (P_{2z}). This figure shows a strong correlation between the momenta of the two electrons. There is a clear maximum for both electrons being emitted with the same momentum component in the direction of polarization axis of about 2.7 *a.u.*, and emission to opposite half planes is strongly suppressed, i.e. both two electrons tend to fly to same side of ion in the direction of polarization. This phenomena has been observed in the 'knee' region for argon.[12] On the other hand, from Fig. 3, we see that the maximum momentum of both electron is about 4.5 *a.u.*, which is consist with the electron-ion coincidence experiment observation of helium,[11] in which the maximum energy of emission electron is $4U_p$, since the perpendicular component of momentum is small, the maximum momentum component in the polarization direction can be approximate obtained as $P_{z\,\max} = \sqrt{8U_p} \simeq 4\ a.u.$

In conclusions, a quasistatic two step model is used to investigate the double ionization of helium in intense linearly polarized field. Our calculations reproduce the excessive double ionization and the photoelectron spectra observed in experiments. We argue that the classical collisional trajectories are the main source of the double ionization in the knee regime and responsible for the unusual angular

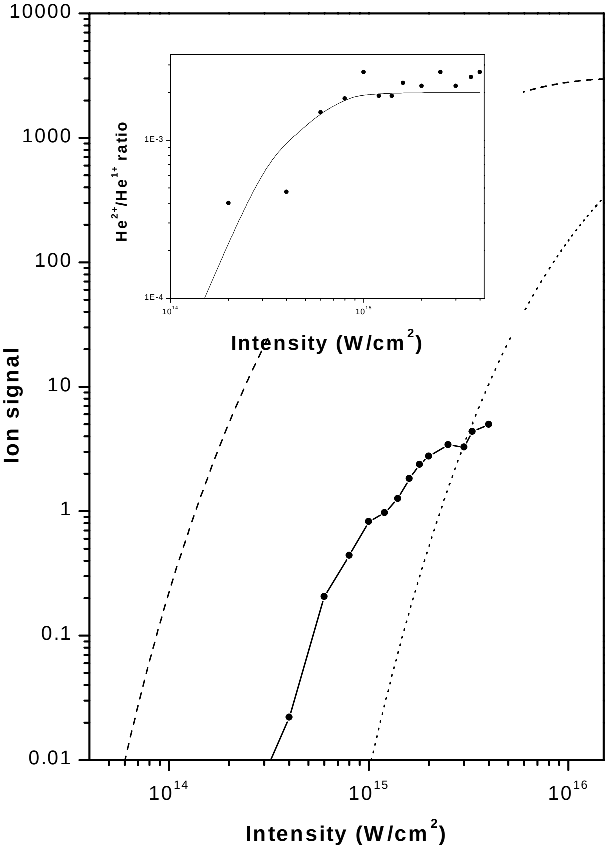

Fig. 1. The dashed and dotted lines correspond to the single ionization yields of He and He^+ predicted by ADK tunneling ionization respectively; The full circles correspond to the results from our model. Inset: Intensity dependence of $\mathrm{He}^{2+}/\mathrm{He}^+$ ratio given by our model. The solid line is gotten from the experiment.[2]

distribution of the photoelectrons. Two distinguished typical collisional trajectories correspond to the 'recollision' process and the 'shake-off' process respectively. Both of the two processes have contribution to the double ionization, but the 'recollision' gives the main contribution and leads to more than 80% of the double ionization yields. We also found the momentum correlation between magnitude and direction of the two emission electron. Because the difference momentum is only determined by the ionization process, so it is important to verify the dominating process in the "knee" regime. Based on the rescattering model, we argue that the maximum difference momentum of the two emission electrons is $|P^-|_{\max} = 2\sqrt{3.2U_p - I_{p2}}$. We must point out here, the detail discussions of the properties can be found in our other papres.[13] We hope our discussions will stimulate the experimental works in the direction.

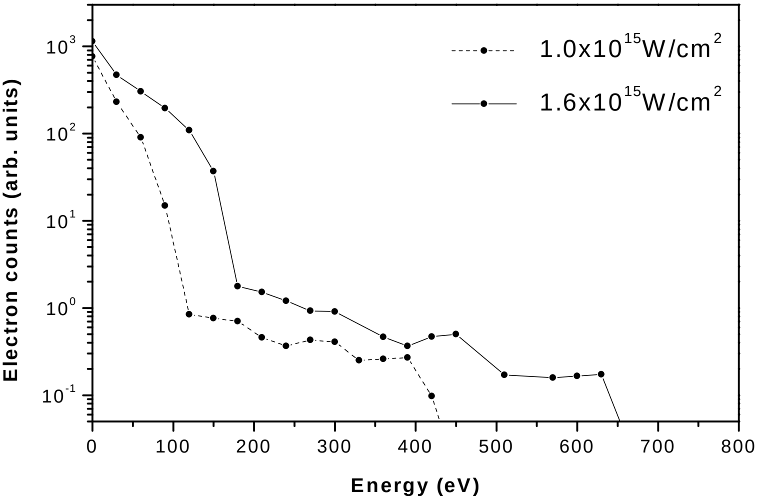

Fig. 2. Photoelectron energy spectra calculated from our model.

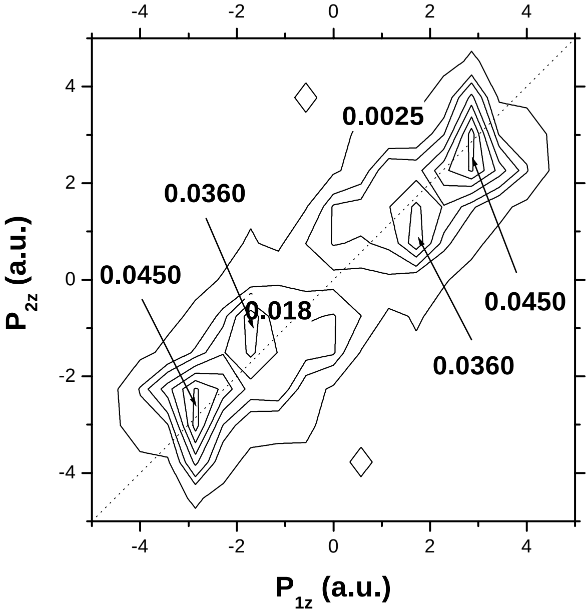

Fig. 3. Momentum correlation between the two emitted electrons given by present calculations.

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