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Wavelength dependence of the Two Channels for Double Ionization of He in Intense Laser Field

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Abstract. In this paper, we investigate the double ionization process of He for the shakeoff (SO) and correlated energy-sharing (CES) channels in intense laser field based on the intense-field many body S-matrix theory (IMST). The wavelength dependence of the ionization rate from these two channels are analyzed and compared with each other. According to our calculation, the CES channel dominants at long wavelengths (300-780nm), while the SO channel dominants at short wavelengths (20-200nm). The more interesting thing occurs in the intermediate wavelength regime (200-300nm) where the contributions from the SO and CES channels are comparable and may compete with each other.

1. Introduction

The intense infrared laser-induced double ionization of atoms has been investigated extensively from both experiments and theoretical aspects during the past four decades [1-22]. Various mechanisms, such as "shakeoff" [3], "collective tunneling" [4], "rescattering model" [5] and so on, are proposed to interpret the experimental phenomena. And it has been accepted that rescattering is the dominant mechanism for the so called "non-sequential" double ionization phenomenon which mainly occuring at infrared wavelength [7,12-13]. From the aspect of S-matrix theory, the shakeoff mechanism corresponds to the first-order term (shakeoff channel) while the rescattering mechanism relates to the second-order term (correlated energy-sharing channel). Actually, both channels contribute to the double ionization process and the relative contribution is dependent on the laser parameters [15].

So far, much progress of the double ionization has been reported at infrared wavelength [7,9,13-15]. For two electron energy distributions of the double ionization in He, the calculations from the SO channel are ruled out and those from the CES channel are in good agreement with the experiments at infrared wavelength [14]. Recently, there are also many papers reporting double ionization of He atom at XUV wavelength [23-25]. Recoil-ion momentum distributions are measured, where the absorption of two photons results in double ionization of He. Then, good agreement with the results of a model calculation is observed for direct ionization [23]. However, there is few work focusing on the double ionization in the regime of intermediate wavelength where the contributions from the SO and CES channels are comparable.

In this paper, we analyze the relative contribution of the total double ionization rates of the SO and CES channels in intense laser field whose wavelength ranges from XUV to Infrared. The IMST theory is used to study the dependence of the double ionization rate of He atom at the wavelengths (20-780nm) in linearly polarized field. We find that the contribution of the total ionization rate from the SO channel is several orders of magnitude higher than that from the CES at short wavelengths (20-200nm). In contrast, the contribution of the total ionization rate from the SO channel is many orders of magnitude lower than that from the CES at long wavelengths (300-780nm). It can be found that the two channels may compete with each other at the intermediate wavelengths (200-300nm).

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2. Theoretical methods

By absorption of N photons, the differential rate formula of double ionization of He in an intense linearly polarized laser field can be expressed as [10,14]

$$\frac{dW}{dk_a k_b} = \sum_N 2\pi\delta\left(\frac{k_a^2}{2} + \frac{k_b^2}{2} + E_{1s} + 2U_p - N\omega\right)\left|T_N(k_a,k_b)\right|^2 \quad , \tag{1}$$

where, T_N of the SO channel which can be write as follows,

$$\begin{aligned} T_N^{SO}(k_a,k_b) = &\sum_n J_{N-n}(\alpha_0 \cdot k_a; \frac{U_p}{2\omega}) J_n(\alpha_0 \cdot k_b; \frac{U_p}{2\omega}) \\ &\times\left[U_p - (N-n)\omega\right]\left\langle \phi_f^0(k_a,k_b;r_1,r_2)\middle|\phi_{1s}(r_1,r_2)\right\rangle) \end{aligned} \quad , \tag{2}$$

and T_N of the CES channel,

$$\begin{aligned} T_N^{CES}(k_a,k_b) = &\sum_j \int \left\langle \phi_f^0(k_a,k_b;r_1,r_2)\middle|\frac{1}{r_{12}}\middle|\phi^0(k,r_1)\phi_j(r_2)\right\rangle \\ &\times \sum_n \left(U_p - N\omega\right)\frac{J_{N-n}(\alpha_0 \cdot (k_a + k_b - k); \frac{U_p}{2\omega})}{\left(\frac{k^2}{2} - E_j + E_{1s} + U_p - n\omega\right)} \\ &\times J_n(\alpha_0 \cdot k; \frac{U_p}{2\omega})\left\langle \phi^0(k,r_1)\phi_j(r_2)\middle|\phi_{1s}(r_1,r_2)\right\rangle \end{aligned} \quad , \tag{3}$$

Here, $\phi^0(k,r_1)$ is the Volkov wave function of one electron ejected, and $\phi_f^0(k_a,k_b;r_1,r_2)$ is the final Volkov wave state with two electrons ejected [15]. $\phi_{1s}(r_1,r_2)$ is the ground state wave function with binding energy E1S=2.904(a.u.), $\phi_j(r_2)$ is the binding state of the He+ ion with binding energy Ej. Both of them are s-wave states.

By assuming the hydrogen like model, these wave functions are calculated as follows,

$$\begin{aligned}&\langle\phi^0(k,r_1)\phi_j(r_2)|\phi_{1s}(r_1,r_2)\rangle\\&=\int dr_1^3\int dr_2^3 e^{-ik\cdot r_1}\left(\frac{z_2^3}{\pi}\right)^{1/2}e^{-z_2r_2}\left(\frac{z_1^3}{\pi}\right)^{1/2}e^{-z_1r_1}\left(\frac{z_1}{\pi}\right)^{1/2}e^{-z_1r_2},\\&=\frac{32\pi z_1\left(z_1^6z_2^3\right)^{1/2}}{\left(z_1^2+k^2\right)^2\left(z_1+z_2\right)^2}\end{aligned}\tag{4}$$

$$\begin{aligned}&\langle\phi_f^0(k_a,k_b;r_1,r_2)|\phi_{1s}(r_1,r_2)\rangle\\&=\int dr_1^3\int dr_2^3 e^{-ik_a\cdot r_1}e^{-ik_b\cdot r_2}\left(\frac{z_1^3}{\pi}\right)^{1/2}e^{-z_1r_1}\left(\frac{z_1}{\pi}\right)^{1/2}e^{-z_1r_2},\\&=\frac{16\pi z_1^5}{\left(z_1^2+k_a{}^2\right)^2\left(z^2{}_1+k_b{}^2\right)^2}\end{aligned}\tag{5}$$

$$\begin{aligned}&\langle\phi_f^0(k_a,k_b;r_1,r_2)|\frac{1}{r_{12}}|\phi^0(k,r_1)\phi_j(r_2)\rangle\\&=\int dr_1^3\int dr_2^3 e^{-ik_a\cdot r_1}e^{-ik_b\cdot r_2}\frac{1}{r_{12}}e^{-ik\cdot r_1}\left(\frac{z_2^3}{\pi}\right)^{1/2}e^{-z_2r_2},\\&=\frac{16\left(z_2^5\pi^3\right)^{1/2}}{\left[z_2^2+\left(k_a+k_b-k\right)^2\right]^2\left(k_a-k\right)^2}\end{aligned}\tag{6}$$

where z_1 and z_2 are the effective nuclear charges of He^+ and He^{2+} ions, respectively.

Through the radial integration in k_a and k_b to Eq. (1) by pole approximation, the double ionization rates of the two channels are

3. Results and discussion

First, we calculate the double ionization rates of He for the CES and SO channels in intense laser field whose wavelength ranges from XUV to Infrared. The results are shown in Figures 1 and 2. Each curve represents a certain wavelength, which is shown in the legends of the figures. The horizontal axis represents the intensity of laser field, while the vertical axis represents the double ionization rates of He.

In Fig.1, it is clearly seen that the total double ionization rates increase as the field intensity increases for all wavelengths. At the short wavelengths(λ=20, 100, 200nm, and 300nm), the dependence of the ionization rate on the intensity and wavelength is similar to the case in Fig. 1. This is because it falls into the multi-photon ionization regime for short wavelength which can also be described by the perturbative multiple-photon ionization formula. However, for longer wavelengths (λ=500, and 780nm), the curve shows a “knee” structure indicateing that it falls into the tunneling regime where the rescattering mechanism dominates the double ionization.

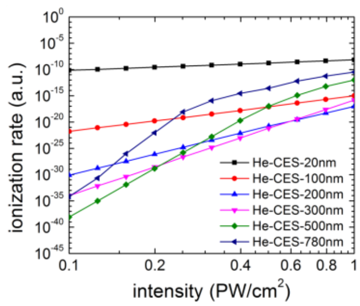

Figure1: Double ionization rates for the CES channel versus laser intensity for He at different wavelengths. λ= 780nm (■), 500nm (●), 300nm (▲), 200nm (▼), 100nm (◆) and 20nm (◄)

In Fig.2, it is found that the double ionization rates from the SO channel increase monotonically with laser intensity for all wavelengths. At the same time, the ionization rates will increase with decreasing wavelength. Moreover, the ionization rate increases faster with intensity for longer wavelength. It can be understood from the perturbative multiple-photon ionization rate formula, $\Gamma_n=\sigma_n \mathrm{I}^{\mathrm{n}}$(n is the number of minimum photon that multiple photon-ionnization needs. Γ_n and σ_n are the total ionization rates and cross sections, respectively.). When fixed wavelength, the ionization rates increase mainly due to the increase of. As we know, the minimum photon number n will decrease with decreasing wavelength. As a result, the ionization rate will increase due to the increasing n-photon ionization cross σ_n section but the rising rate decrease due to I^n.

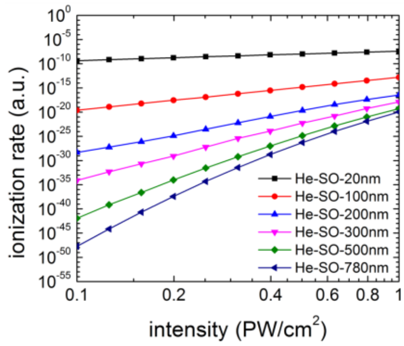

Figure2: Double ionization rates for the SO channel versus intensity for He at different wavelengths. λ=780nm(■), 500nm(●), 300nm(▲), 200nm(▼), 100nm(◆) and 20nm(◄).

Then, we analyse the ratios of double ionization rates between SO channel to those from the CES channel, which are shown in Fig.3. The horizontal axis and the vertical axis represent the intensity of laser field and the ratio, respectively.

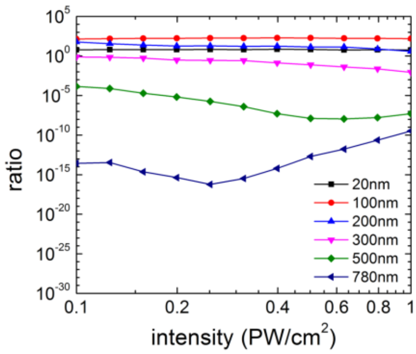

Figure 3: Ratio of intense laser double ionization rates from the SO channel and those from the CES channel versus intensity for He at different wavelengths. λ=780nm (■), 500nm (●), 300nm (▲), 200nm (▼), 100nm (◆) and 20nm (◄).

In Fig.3, it is clearly seen that ratios increase with decreasing wavelength. At the same time, the ratios keep almost invariant against increasing of the laser field intensity at the wavelengths (λ=20, 100, and 200nm). At long wavelengths (λ=500, 780nm), the contributions of the total ionization rates from SO channel are many orders of magnitude lower than that from the CES. At 300nm, contributions of the total ionizations of the total ionization rates from SO channel are little lower than that from the CES. But, contributions of the total ionization rates from the SO channel are several orders of magnitude higher than that from the SO at short wavelengths (λ=20, 100, and 200nm). There exit competition between the two channels when the wavelength ranges from 200nm to 300nm.

Finally, we also calculate two-electron energy spectra from the two channels at intermediate wavelengths of 300nm and 200nm, respectively. The results are shown in Fig.4.

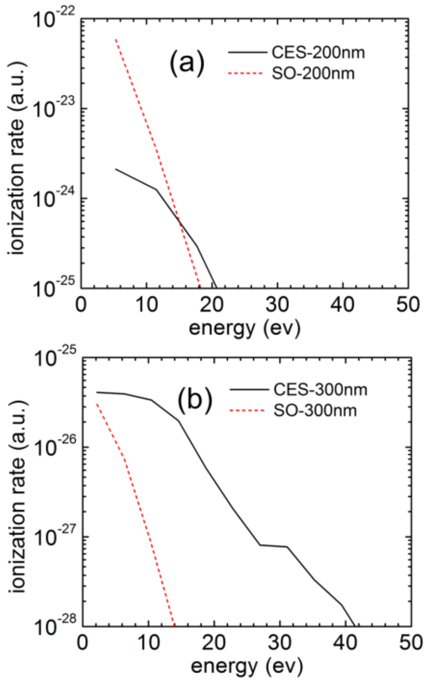

Figure 4: The two-electron energy spectra calculated from the CES channel (solid line) and SO channel (dash line) at an intensity of 3×10^{14}w/cm^2: (a) 200nm, (b) 300nm.

From Fig. 4 we can see that, the contributions from the SO and CES channels are comparable and neither of them can be ignored. Both channels make important contributions to the energy spectrum. The SO channel mainly contributes to the low energy part while the CES channel dominates in the high energy part.

4. Conclusions

In conclusion, we compare the contributions from two channels for He in intense laser field whose wavelength ranges from XUV to infrared. The results show that the ratios keep almost invariant with laser field intensity at wavelengths of 20nm, 100nm and 300nm. We find that the contributions of the total ionization rates from the SO channel are several orders of magnitude higher than that from the CES at these wavelengths. Competition exists between the two channels with intense laser field with wavelength 200nm -300nm.

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References

[1] M. V. Ammosov and N. B. Delone, High Intensity Laser Processes. 664 (1986) 138.
[2] B. Fain, A. Boeglin and S. H. Lin, J. Chem. Phys. 88 (1988) 7559.
[3] D. N. Fittingoff, P. R. Bolton, B. Chang and K. C. Kulander, Phys. Rev. Lett. 69 (1992) 2642.
[4] U. Eichmann et al., Phys. Rev. Lett. 84 (2000) 3550.
[5] P. B. Corkum, Phys. Rev. Lett. 71 (1993) 1994.
[6] K. Kondo, A. Sagisaka, T. Tamida, Y. Nabekawa and S. Watanabe, Phys. Rev. A 48 (1993) R2531.
[7] B. Walker, B. Sheehy, L. F. Dimauro, P. Agostini, K. J. Schafer and K. C. Kulander, Phys. Rev. Lett. 73 (1994) 1227.
[8] A. Becker and F. H. M. Faisal, J. Phys. B: At. Mol. Opt. Phys. 29 (1996) L197.
[9] A. Becker and F. H. M. Faisal, Phys. Rev. A. 59 (1999) R59.
[10] A. Becker and F. H. M. Faisal, Phys. Rev. Lett. 84 (2000) 3546.
[11] J. Chen, J. Liu, L. B. Fu and W. M. Zheng, Phys. Lett. A. 63 (2000) 011404(R).
[12] R. Dörner,, V. Mergel, O. Jagutzki, L. Spielberger, J. Ullrich, R. Moshammer and H. Schmidt-Böcking, Phys. Rep. 330 (2000) 95.
[13] R. Lafon, J. L. Chaloupka, B. Sheehy, P. M. Agostini, K. C. Kulander and L. F. DiMauro, Phys. Rev. Lett. 86 (2001) 2762.
[14] A. Becker and F. H. M. Faisal, Phys. Rev. Lett. 89 (2002) 193003.
[15] A. Becker and F. H. M. Faisal, J. Phys. B: At. Mol. Opt. Phys. 38 (2005) R1.
[16] X. L. Hao, G. Q. Wang, X. Y. Jia, W. D. Li, J. Liu and J. Chen, Phys. Rev. A 80 (2009) 023408.
[17] X. L. Hao, W. D. Li, J. Liu and J. Chen, Phys. Rev. A 83 (2011) 053422.
[18] W. Becker, X. J. Liu, P. J. Ho and J. H. Eberly, Rev. Mod. Phys. 84 (2012) 1011.
[19] X. L. Hao, X. L. Zhang, W. D. Li and J. Chen, Phys. Rev. A 87 (2013) 045403.
[20] X. L. Hao, J. Chen, W. D. Li, B. Wang, X. Wang and W. Becker, Phys. Rev. Lett. 112 (2014) 073002.
[21] X. M. Ma, Y. M. Zhou and P. X. Lu, Phys. Rev. A 93 (2016) 013425.
[22] M. S. Schöffler, X. H. Xie, P. Wustelt, M. Möller, S. Roither, D. Kartashov, A. M. Sayler, A. Baltuska, G. G. Paulus and M. Kitzler, Phys. Rev. A 93 (2016) 063421.
[23] A. Rudenko et al., Phys. Rev. Lett. 101 (2008) 073003.
[24] F. C. Jin, J. Chen, Y. J. Yang, Z. C. Yan and B. B. Wang, J. Phys. B: At. Mol. Phys. 49 (2016) 195602.
[25] F. C. Jin, Y. Y. Tian, J. Chen, Y. J. Yang, X. J. Liu, Z. C. Yan and B. B. Wang, Phys. Rev. A 93 (2016) 043417.

