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Dynamic stabilization of Na atom in an intense pulsed laser field*

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We investigate theoretically the ionization properties of the valence electron for the alkali metal atom Na in an intense pulsed laser field by solving numerically the time-dependent Schrödinger equation with an accurate l-dependent model potential. By calculating the variations of the ionization probabilities with laser peak intensity for wavelengths ranging from 200 nm to 600 nm, our results present a dynamic stabilization trend for the Na atom initially in its ground state (3s) and the excited states (3p and 4s) exposed to an intense pulsed laser field. Especially a clear "window" of dynamic stabilization at lower laser intensities and longer wavelengths for the initial state 4s (the second excited state) is found. By analyzing the time-dependent population distributions of the valence electron in the bound states with the different values of principal quantum number n and orbital quantum number l, we can attribute the dynamic stabilization to the periodic population in the low-excited states since the valence electron oscillates rapidly between the lowly excited states and the continuum states.

Keywords: accurate model potential, atomic dynamic stabilization, ionization probability

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1. Introduction

Generally, the ionization probability of atoms exposed to an intense laser field increases as the laser peak intensity increases.[1–3] However, several theorists predicted the existence of stabilization phenomena when an atom is driven by a high-frequency super-intense laser field,[4,5] namely the ionization probability tends to decrease instead of increasing when the laser intensity exceeds a certain value. This unusual behavior of ionization probability versus laser intensity (i.e., stabilization) of atoms and molecules has aroused a great deal of interest from many researchers in the past three decades. So far the stabilization of atoms and molecules has been widely studied theoretically. The quasistationary (adiabatic) stabilization (QS) of the ground-state atoms was proposed to be studied by using the high-frequency Floquet theory (HFFT),[6] while the dynamic stabilization (DS) has been widely investigated by solving the one-dimensional (1D), two-dimensional (2D), or three-dimensional (3D) time-dependent Schrödinger equation (TDSE) based on the dipole approximation (DA) mostly in the Kramers–Henneberger (KH) frame.[7–14] Furthermore, the validity of the dipole approximation in the stabilization regime has been questioned and examined by comparing the DA results with those obtained from the nondipole approximation.[15–17] The laser conditions for the DS have been mapped out by solving numerically the TDSE, and the DS was explained reasonably with the time-averaged KH potential. It has been predicted theoretically that there exists a very clear ground-state stabilization of a hydrogen atom in a circularly polarized laser field if the appropriate laser parameters are used.[5] However, only a few experiments were performed for the Rydberg atoms (see, e.g., the review papers[18–20] and references therein), while the stabilization of other atoms initially in the ground state or the lower excited states is still difficult to observe in an experiment because the atoms can be ionized completely during the rising edge of the intense pulsed laser.

The reason why the stabilization of the Rydberg atoms in the laser field can be observed experimentally is that the Rydberg atom has lower ionization energy.[21] For the alkali metal atoms, they also have the lower ionization potentials both for initially the ground state and the lowly excited states. We estimate the possibility of stabilization of the alkali metal atoms (for example, Na) exposed to an intense pulsed laser. In this paper, we investigate the DS of the excited Na atom in an intense laser field, by solving the TDSE combined with an accurate model potential, which can be observed with the presently available laser pulses. Atomic units are used throughout this paper unless otherwise stated.

2. Theoretical method

Under the dipole approximation and the length gauge, the one-electron 3D time-dependent Schrödinger equation of the Na atom can be written as

$$\mathrm{i}\frac{\partial}{\partial t}\psi(\boldsymbol{r},t)=\left[\hat{H}_0+\hat{V}(\boldsymbol{r},t)\right]\psi(\boldsymbol{r},t), \tag{1}$$

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where $\hat{H}_0$ is the unperturbed Hamiltonian

$$H_0 = -\frac{1}{2}\nabla^2 + \sum_l |Y_l^0\rangle V_l \langle Y_l^0| . \tag{2}$$

where, V_l is an angular-momentum-dependent model potential,[22] which can give accurate bound-state energies. The V_l has the following form:

$$V_l = -\frac{1}{r} - \frac{\alpha}{2r^4} W_6\left(\frac{r}{r_c}\right) - \left(\frac{N-S}{r} + A_1\right) e^{-B_1 r} - \left(\frac{S}{r} + A_2\right) e^{-B_2 r}, \tag{3}$$

where α and r_c are the dipole polarizability and the effective radius of the Na^+ core, respectively. Here, we take $N = 10$ and other parameters have been documented in Ref. [22]. W_n is a core cutoff function given by

$$W_n(x) = 1 - \left[1 + nx + \frac{(nx)^2}{2!} + \cdots + \frac{(nx)^n}{n!}\right] e^{-nx}. \tag{4}$$

The atom-field interaction $\hat{V}(\boldsymbol{r},t)$ can be described in the length form as

$$\hat{V}(\boldsymbol{r},t) = \boldsymbol{r}\cdot\boldsymbol{E}(t). \tag{5}$$

For a linearly polarized laser pulse (along the z axis) with carrier frequency ω and carrier-envelope phase (CEP) φ, the electric field $\boldsymbol{E}(t)$ is taken to be in the following form:

$$\boldsymbol{E}(t) = \hat{z}E_0 \sin^2\left(\frac{\pi t}{\tau}\right)\cos(\omega t + \varphi) \tag{6}$$

for the time interval (0, τ), and zero elsewhere. The full width at half maximum (FWHM) of the intensity is given by $\Gamma = \tau/2.75$. The CEP φ is taken to be 0 in this paper.

Equation (1) can be numerically solved by using the time-dependent generalized pseudospectral (TDGPS) method.[23,24] To avoid the artificial reflection due to a finite box size, we use the following absorbing function: $\cos^{1/4}[\pi(r - r_{cut})/2(r_{max} - r_{cut})]$ for $r \geq r_{cut}$. In the present calculations, we typically choose $r_{max} = 400$ a.u., (unit a.u. is short for atomic unit), $r_{cut} = 380$a .u., the total number of radial grid points $N = 800$, and up to 80 partial waves. Once the time-dependent wave function $\psi(\boldsymbol{r},t)$ is obtained, the time-dependent population of bound states with the principal quantum number n and the orbital quantum number l can be calculated from

$$P_{nl}(t) = |\langle\phi_{nl}(\boldsymbol{r})|\psi(\boldsymbol{r},t)\rangle|^2. \tag{7}$$

Then the time-dependent ionization probability of the Na atom is given by

$$P(t) = 1 - \sum_{nl} P_{nl}(t), \tag{8}$$

and the ionization probability of the Na atom at the end of the pulse for a certain laser intensity can be obtained to be $P(t)|_{t=\tau}$, where τ is the time of the laser pulse ending.

3. Results and discussion

Using Eq. (8), we have calculated the ionization probabilities of the Na atom at the end of laser pulses for various peak intensities. In our simulations, an 8-cycle short laser pulse with a central wavelength of 400 nm is used. Figure 1 shows the dependence of ionization probability of the Na atom on the laser peak intensity. In Fig. 1(a), we compare the laser-intensity-dependent ionization probabilities of the Na atom for different initial states (i.e., 3s, 4s, and 3p). Clearly all the ionization probabilities firstly increase, then decrease and finally increase as the laser intensity is increased (i.e., a "window" of DS exists). If the Na atom is initially prepared in the ground state 3s or the first excited state 3p, the "window" of DS is located at a higher laser intensity about 1.0×10^{16} W/cm^2. However, the "window" of DS is shown up at the lower laser intensity around 2.6×10^{15} W/cm^2, when the Na atom is completely populated in the initial second excited state 4s, which can be observed easily with the present femetosecond (fs) lasers. In Fig. 1(b) we demonstrate how the position of the "window" of DS depends on the laser wavelength by taking the initial 4s state of the Na atom for example. One can see that the width of the "window" increases gradually and the "window" shifts toward the higher laser intensity as the laser wavelength decreases. It indicates that the requirement of the stabilization "window" for the laser intensity can be reduced remarkably if the longer wavelength is used.

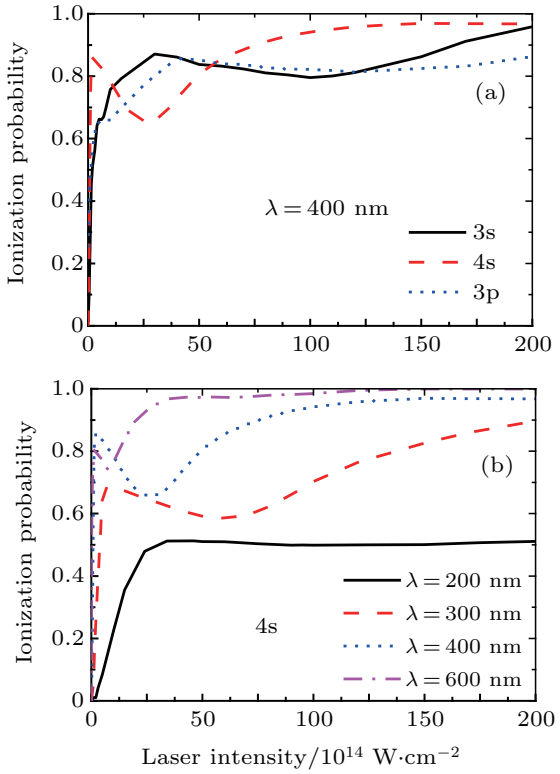


Fig. 1. (color online) Variations of ionization probability of the Na atom with laser peak intensity, for (a) 3s, 4s, and 3p initial states at 400 nm and (b) 4s initial state at four different laser central wavelengths of 200, 300, 400, and 600 nm.

In the following discussions, we will explain the reason why the excited Na atom can be stabilized dynamically by taking the 4s initial state driven by 400-nm laser pulse for example.

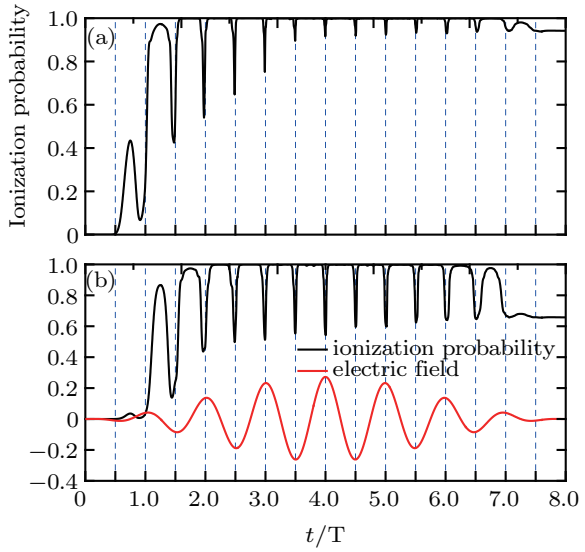


Fig. 2. (color online) Time-dependent ionization probabilities of the Na atom with initial 4s state in the laser field with a central wavelength of 400 nm and laser peak intensities of (a) 1.0×10^{16} W/cm^2 and (b) 2.6×10^{15} W/cm^2. The corresponding electric field of laser pulse at 2.6×10^{15} W/cm^2 is also given.

Figures 2(a) and 2(b) show the time-dependent ionization probabilities of the Na atom at two different laser peak intensities, i.e., 1.0×10^{16} W/cm^2 and 2.6×10^{15} W/cm^2, respectively. In Fig. 2(a), one can see that the Na atom is almost completely ionized at the end of the laser pulse and the final survival probability is only 5.8% for the laser peak intensity of 1.0×10^{16} W/cm^2 which is away from the "window" of DS. However, the Na atom can be well stabilized dynamically and the final survival probability can reach up to 34.2% if the Na atom driven by a laser field with the intensity of 2.6×10^{15} W/cm^2, which is located in the center of the "window" of DS (see Fig. 1(b)). It is clear that the ionization probability oscillates rapidly with time and the oscillation period is just half the period of laser pulse.

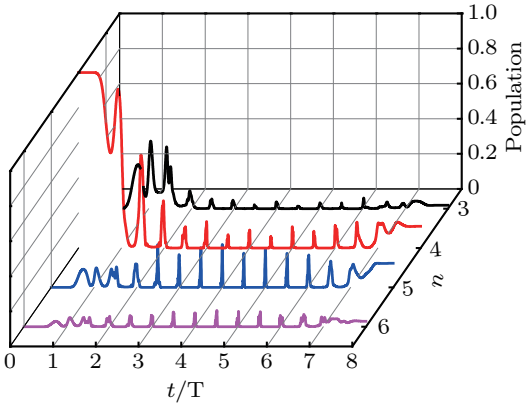


Fig. 3. (color online) Time-dependent population distributions in bound states with different values of principal quantum number n for the Na atom. The laser parameters are the same as those in Fig. 2(b).

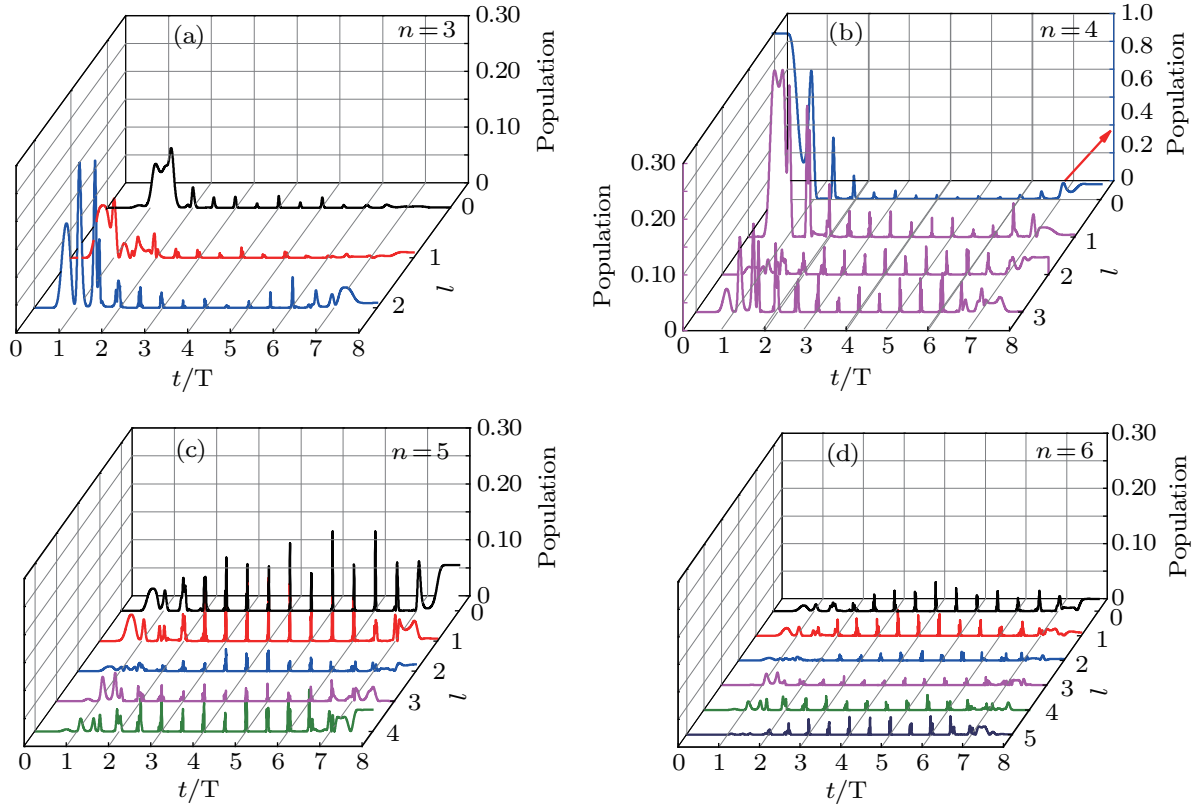


Fig. 4. (color online) Time-dependent population distributions in bound states with different values of n and l for the Na atom. The laser parameters are the same as those in Fig. 2(b).

To understand the oscillations of the time-dependent ionization shown in Fig. 2, by using Eq. (7), we calculate the time-dependent population distributions of the bound states with different values of principal quantum number n and orbital angular momentum quantum number l for the Na atom with the initial 4s state. Figure 3 presents the time-dependent population distributions in bound states. Clearly the population in bound states with $n = 3$ and $n = 4$ is dominant on the rising edge of the laser pulse. Then, the valence electron is populated mainly in lowly excited states with $n = 4$ and 5 under the present laser conditions. The final population of excited states is 12.4% for $n = 4$, and it is 13.7% for $n = 5$. In Fig. 4, we also show the population distributions of different values of l with $n = 3$, 4, 5, and 6 of the bound states and find the distribution of $l =$ odd number tends to zero, which is consistent with the single-photon process as the initial state is 4s.[25] Comparing Fig. 3 with Fig. 2, we can see that the smaller the distribution of continuous states, the larger the distribution of the low-bound states is, which means that the valence electron of the Na atom with a very large acceleration can be released into the continuum state and then it can be driven back and combined with the parent ion into lowly bound states in a very short time. So the dynamic stabilization of the excited Na atom exposed to laser pulse can be attributed to the periodic population in its lowly excited state.

4. Conclusions

In this paper, we study theoretically the dynamic stabilization of the Na atom in an intense short laser field with the central wavelengths ranging from 200 nm to 600 nm by solving numerically the three-dimensional time-dependent Schrödinger equation with an accurate$l$-dependent model potential. By calculating the variation of the ionization probability with laser peak intensity, a clear "window" of dynamic stabilization is found at the lower laser intensity and longer wavelength if the Na atom is initially prepared in the second excited state 4s, and the "window" shifts toward higher laser intensity as the wavelength decreases. By analyzing the time-dependent population distributions of the valence electrons for different values of principal quantum number n and orbital quantum number l, we can attribute the dynamic stabilization to the periodic population in lower excited states because the valence electrons oscillate rapidly between the lowly excited states and the continuum states. We mention that the dynamic stabilization of the excited Na atom in an intense visible (400 nm) short laser pulse can be observed in an experiment by using the present available lasers, while dynamic stabilization of the ground-state alkali metal atoms is still difficult to observe in an experiment because the driven intensity of laser pulse is strong.

References

[1] Tian Y Y, Li S Y, Wei S S, Guo F M, Zeng S L, Chen J G and Yang Y J 2014 *Chin. Phys. B* **23** 053202
[2] Liu M, Guo Y C and Wang B B 2015 *Chin. Phys. B* **24** 073201
[3] Tu X H, Hao X L, Li W D, Hu S L and Chen J 2016 *Chin. Phys. Lett.* **33** 093201
[4] Fedorov M V and Movsesian A M 1988 *J. Phys. B: At. Mol. Opt. Phys.* **21** L155
[5] Pont M and Gavrila M 1990 *Phys. Rev. Lett.* **65** 2362
[6] Gavrila M 1992 *Atoms in Intense Laser Fields*, ed. M Gavrila (New York: Academic) p. 435
[7] Su Q, Eberly J H and Javanainen J 1990 *Phys. Rev. Lett.* **64** 862
[8] Vivirito R M A and Knight P L 1995 *J. Phys. B: At. Mol. Opt. Phys.* **28** 4357
[9] Zhou X X, Li B W and Lin C D 2001 *Phys. Rev. A* **64** 043403
[10] Protopapas M, Lappas D G and Knight P L 1997 *Phys. Rev. Lett.* **79** 4550
[11] Horbatsch M 1991 *Phys. Rev. A* **44** R5346
[12] Tang X and Basile S 1991 *Phys. Rev. A* **44** R1454
[13] Volkova E A, Popov A M and Tikhonova O V 2001 *JETP* **93** 1155
[14] Dondera M, Muller H G and Gavrila M 2002 *Phys. Rev. A* **65** 031405
[15] Latinne O, Joachain C J and Dörr M 1994 *Europhys. Lett.* **26** 333
[16] Kylstra N J, Worthington R A, Patel A, Knight P L, Vázquez de Aldana J R and Roso L 2000 *Phys. Rev. Lett.* **85** 1835
[17] Simonsen A S and Førre M 2015 *Phys. Rev. A* **92** 013405
[18] Delone N B and Krainov V P 1995 *Phys. Usp.* **38** 1247
[19] Gavrila M 2002 *J. Phys. B: At. Mol. Opt. Phys.* **35** R147
[20] Popov A M, Tikhonova O V and Volkova E A 2003 *J. Phys. B: At. Mol. Opt. Phys.* **36** R125
[21] de Boer M P, Hoogenraad J H, Vrijen R B, Noordam L D and Muller H G 1993 *Phys. Rev. Lett.* **71** 3263
[22] Chu X, Chu S I and Laughlin C 2001 *Phys. Rev. A* **64** 013406
[23] Tong X M and Chu S I 1997 *Chem. Phys.* **217** 119
[24] Zhao S F, Zhou X X, Li P C and Chen Z 2008 *Phys. Rev. A* **78** 063404
[25] Chen Z, Morishita T, Le A T, Wickenhauser M, Tong X T and Lin C D 2006 *Phys. Rev. A* **74** 053405