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Laser pulse design for coherent laser control of potassium atoms*

Zhang Xian-Zhou(张现周), Jia Guang-Rui(贾光瑞)†, and He Hai-Fang(何海芳)

Department of Physics, Henan Normal University Xinxiang 453007, *China*

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In this paper, the dynamics of coherent laser control of potassium atoms is studied by using the time-dependent multilevel approach (TDMA). The calculation results of population transfer are presented with different laser fields. The results show that the population can be transferred to target state completely by a specially designed laser field.

Keywords: time-dependent multilevel approach (TDMA), coherent laser control, population transfer, specially designed laser field

PACC: 3100, 1240Q, 3280K

1. Introduction

During the past decades, coherent laser control of the quantum states has opened up undreamed-of prospects for application in a variety of fields such as laser control of chemical reactions, atom optics, high precision metrology, and quantum computing.[1] Coherent laser control of the quantum states deals with the design of suitably shaped laser fields to selectively steerable quantum system from an initial state to a desired final state with high efficiency. It is well known that stimulated Raman adiabatic passage works perfectly in the population transfer of an atomic system,[2−8] which demonstrates that two laser pulses should be involved, and a counterintuitive pulse is more efficient and easy to realize than the intuitive one in transferring population and coherence. Recently, the ability to coherently manipulate quantum systems in a controlled fashion by using only a single frequency-chirped laser pulse has become a goal of the highest priority.[9] The results show that an optimized population transfer scheme has been presented, and confirm that intuitive laser pulse can also be used in three-lever-Λ system to manipulate quantum states with high efficiency, in which the configuration of quantum states is used in stimulated Raman adiabatic passage (STIRAP) experiment.[1] However, these analytical studies were performed in adiabatic passage in an ideal system which includes only assumed coupled states,[10] while the effects of other states were ignored. In this paper, using the time-dependent multilevel approach (TDMA) method and a number of coupled states instead of only the considered involved states, we will calculate population transfer among the quantum states of Rydberg potassium atoms irradiated by a specially designed laser pulses.[11] A class of laser pulses and their specially designed resonant frequency with two-level systems and three-level systems are considered. The goal of the present paper is twofold: the first is to achieve as complete as possible population transfer between the selected states of potassium atoms, the second is to make this transfer as rapid as possible. Because the life of Rydberg states is much longer than the delay time of the laser pulse, the spontaneous radiation can be ignored and the course is considered as adiabatic. With a class of pulses of arbitrary shape and duration, the frequency can be specially designed to maximize the population transfer amplitude, and the population trapping can be realized in the life of the state. The potassium is exposed to static electric fields and interacts with a specially designed laser field; we expect to find the condition and probability to maximize the population transfer amplitude between the selected Stark states of Rydberg potassium atom for arbitrary laser pulse.

2. Theory and method

In general, the experimental schematic diagram is shown in Fig.1, in the experiment of excitation of

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†E-mail: jgr@henannu.edu.cn

atom. The interaction between atoms and laser fields takes place inside a piece of WR137 waveguide. The potassium atoms effused from a resistively heated oven enter the waveguide through a small hole on one of its sides and the laser pulse enters the waveguide through a hole on the opposite side.

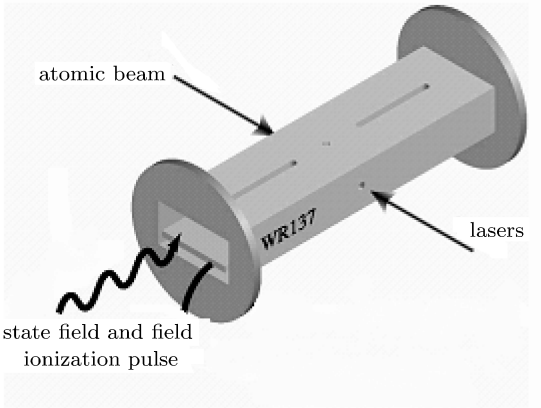


Fig.1. The schematic diagram of the experimental apparatus, in which the interaction takes place. It is a piece of WR137 waveguide with a septum and holes to couple in the fields, lasers and atoms used in the experiment.

The driving laser pulse is designed as

$$E(t) = E_0 m(t) \cos[\omega(t)t], \tag{1}$$

where E_0 is the intensity of laser field, $m(t)$ is the laser pulse shape, $\omega(t)$ is the time dependent carrier frequency. We analyse three types of laser pulse: square laser pulse shape, $m(t) = 1$; sine laser pulse shape, $m(t) = 1 + \sin(\pi t/T)$; Gaussian laser pulse, $m(t) = \exp(t^2/T^2)$, where T is the duration of laser pulses and $\omega(t)$ is carrier frequency. In the presence of a static electric field F_s (the direction of the field is along the z-axis) and a laser field $E(t)$, the Hamiltonian for the outer electron of the potassium atom takes the form

$$H = H_0 + zF_s + zE(t), \tag{2}$$

where H_0 is the field-free Hamiltonian and can be written as

$$H_0 = -\frac{1}{2}\nabla^2 + V(r). \tag{3}$$

The core potential of an alkali-metal atom which involves the effects of penetration and polarization is assumed to be[12]

$$V(r) = -\frac{2}{r}\Big(1 + \frac{\beta'}{(r+\gamma')^2} + \frac{\kappa'}{(r+\xi')^2}\Big). \tag{4}$$

Using this potential, when the atom is in the absence of electric field and laser field, its corresponding field-free Schrödinger equation can be written as

$$H_0 \Phi_i = E_i^0 \Phi_i. \tag{5}$$

So the wavefunction Φ_i of H_0 can be obtained, which has the form $\Phi_i = R_{nl}(r)Y_{lm}(\theta,\phi)$, where $Y_{lm}(\theta,\phi)$ is a spherical harmonic function and $R_{nl}(r)$ has the form

$$R_{nl}(r) = N\exp(-\rho/2)\rho^s(\rho+\gamma)^t(\rho+\xi)^u \sum_{\nu=0} a_\nu \rho^\nu, \tag{6}$$

in which $\rho = \alpha r$, $\gamma = \alpha\gamma'$, $\xi = \alpha\xi'$, $\alpha = 2/(n-\mu_{nl})$, where $s, t, u, \alpha_v, \beta', \gamma', \kappa'$ and ξ' are the parameters to be determined, which depend on n and l; μ_{nl} is a quantum defect value to input. Substituting $R_{nl}(r)$ and $V(r)$ into the radial Schrödinger equation, and considering the standard conditions for a radial wavefunction, we obtain nonlinear algebraic equations for the above parameters. Solving them, we get $s, t, u, \alpha_v, \beta', \gamma', \kappa'$ and ξ', and then $R_{nl}(r)$ and $V(r)$ in their analytical forms. See He *et al*[12] for details.

In the ideal consideration, the basis set should run from $n = 0$ to $n = \infty$, but this can hardly be realized. In order to save the computation significantly with little accuracy lost, we chose 78 field-free wave functions of the potassium atom in the vicinity of 21s and 19g states as a basis set. See Zhang *et al*[13] for details.

Using the above model and the 78 field-free wavefunctions, $\Phi_i = |nlm\rangle$, as a basis set, we find the matrix elements of the Hamiltonian, $H_1 = H_0 + zF_s$, has the following form:

$$H_{1\,nlm,n'l'm} = -\frac{\delta_{nlm,n'l'm}}{2(n-\mu_{nl})^2} + F_s\langle nlm|z|n'l'm\rangle\,. \tag{7}$$

By diagonalizing the matrix of H_1, we can obtain the eigenvalue E_k and eigenvector $\psi_k^{(s)}$ of H_1. They obey the following equation:

$$H_1\psi_k^{(s)} = E_k\psi_k^{(s)}\,, \tag{8}$$

where

$$\psi_k^{(s)} = \sum_{i=1}^{78} C_{ki}\,\Phi_i. \tag{9}$$

Using $\psi_k^{(s)}$ as the new basis set, we can write the wavefunction of the potassium atom in the presence of the static field, together with $E(t)$, can be written as

$$\psi(t) = \sum_{k=1}^{78} a_k(t)\psi_k^{(s)} \mathrm{e}^{-\mathrm{i}E_k t}\,\Phi_i\,, \tag{10}$$

where $a_k(t)$ is the coefficient of the expansion, which represents the amplitude of transition probability, $\mathrm{e}^{-\mathrm{i}E_k t}$ contains the phase information then determines the moment when the resonance occurs. $\psi(t)$ obeys

the time-dependent Schrödinger equation (in atomic mass units):

$$\mathrm{i}\frac{\partial\psi(t)}{\partial t} = H\psi(t)\,. \tag{11}$$

Substituting Eq.(10) into Eq.(11) and solving the time-dependent Schrödinger equation numerically, we can get $a_k(t)$. Then the probability of the outer electron inhabiting the state k can be written as

$$p_k = |a_k|^2. \tag{12}$$

Using the above formula, we can calculate the state-to-state transition probability, from which the amplitude of population transfer and the variation of population of each state can be observed.

3. Result and discussion

In this section, numerical simulations of system dynamics for resonant and coherent laser control of the quantum states are presented. Three configurations of potassium atoms used in the calculation are all labelled as shown in Fig.2.

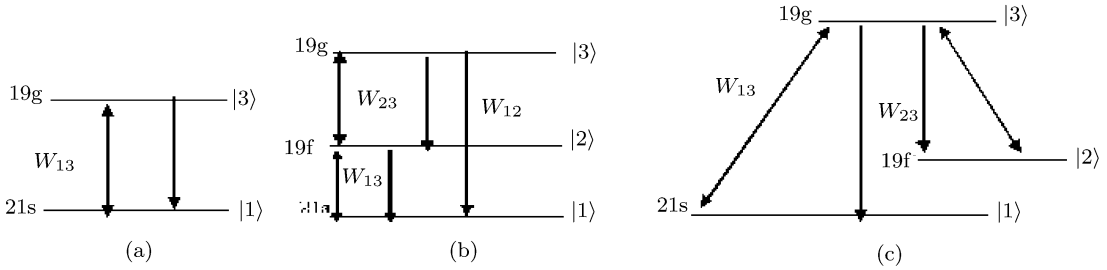


Fig.2. Three configurations of potassium atom in our calculation: (a) two-level system; (b) three-level-ladder system; (c) three-level-Λ system, where W_{12} is the resonant frequency between 21s and 19f states, W_{13} is the resonant frequency between 21s and 19g states, W_{23} is the resonant frequency between 19f and 19g states.

3.1. Two-level system

In the two-level system, by using the above formula, we compare the square pulse shape $m(t) = 1$ with the sine pulse shape $m(t) = 1 + \sin(\pi t/T)(T = 100$ ns). It is assumed that state 21s is initially populated. Setting the static electric field $F_s = 289$ V/cm and $E_0 = 10$ V/cm, letting $\omega(t)$ to be a constant and tune its value $\omega(t) = 33.1023$ GHz according to the Stark splitting between the state 21s and 19g, we calculate the population of state 19g for the different laser pulse shape. When $m(t) = 1$, the amplitude of population and Rabi-like oscillation frequency are constant. While using sine pulse shape, we find that the amplitude of population transfer becomes big and Rabi-like oscillation frequency is no longer a constant. This is because the variation of the laser field had the effect of modulating the energy separation between the two states.[14] The numerical result is shown in Fig.3, which is the same as the optimization calculation result of Ref.[11].

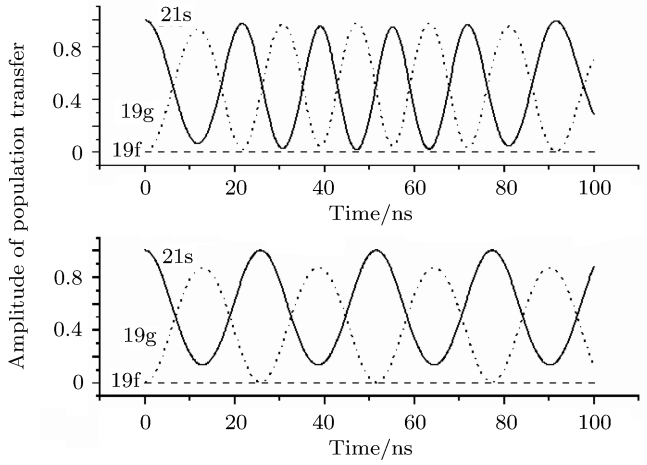


Fig.3. Comparison of amplitude of population transfer and Rabi-like oscillation frequency between square pulse: $m(t) = 1$ (the lower one), and sine pulse: $m(t) = 1 + \sin(\pi t/T)(T = 100$ ns) (the upper one).

3.2. Three-level-ladder system

The three-level system offers a much higher parameter space and richness in physics than the two-level system. In this section, we discuss the ladder-type configuration with the system structure as shown in Fig.1(b). First the square laser pulse is used. By changing the parameters of laser field, we can realize the complete population transfer. The value of E_0 and $\omega(t)$ is as follows: when $0 \leq t \leq 6.4$ ns, E_0= 7.23646 V/cm, $\omega(t) = 7.995566$ GHz, while $6.4 \leq t \leq 9$ ns, E_0= 17.23646 V/cm, $\omega(t) = 25.1013$ GHz, otherwise, E_0= 7.23646 V/cm, $\omega(t) = 7.995566$ GHz. In all the above cases, $m(t) = 1$. Interacting with this laser field, the potassium atom is first pumped from 21s state to 19f state and subsequently from 19f state into 19g state. Complete population transfer into 19g state is achieved. The value of $\omega(t)$ is set to be the resonant frequency between two selected states. The calculation result is shown in Fig.4. Interacting with this specially designed laser field, the population transfer is efficient and almost complete, the population is trapped in 19g states eventually.

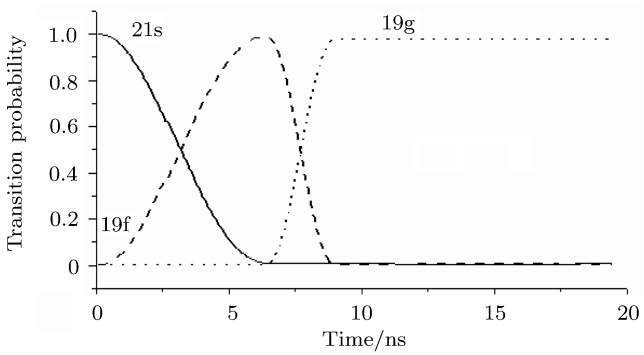


Fig.4. The populations of three states in potassium atom of there-level-ladder system. The solid line, dashed line and dotted line correspond to the population of 21s, 19f and 19g states respectively.

And then the sine pulse shape, $m(t) = 1 + \sin(\pi t/T)$ ($T = 20$ ns), and Gaussian pulse shape, $m(t) = \exp(t^2/T^2)(T = 20$ ns), are used; the parameters are as follows. For Fig.5: $E_0 = 8.236$ V/cm, when $0 \leq t \leq 4.6$ ns, $\omega(t) = 7.995566$ GHz; when $4.6 \leq t \leq 7.5$ ns, $\omega(t) = 25.1013$ GHz; when $t \geq 7.5$ ns, $\omega(t) = 7.995566$ GHz. For Fig.6, $E_0 = 8.5$ V/cm, when $0 \leq t \leq 5.6$ ns, $\omega(t) = 7.995566$ GHz; when $5.6 \leq t \leq 9.7$ ns, $\omega(t) = 25.1013$ GHz. when $t \geq 9.7$ ns, $\omega(t) = 7.995566$ GHz. The calculation results are shown in Figs.5 and 6.

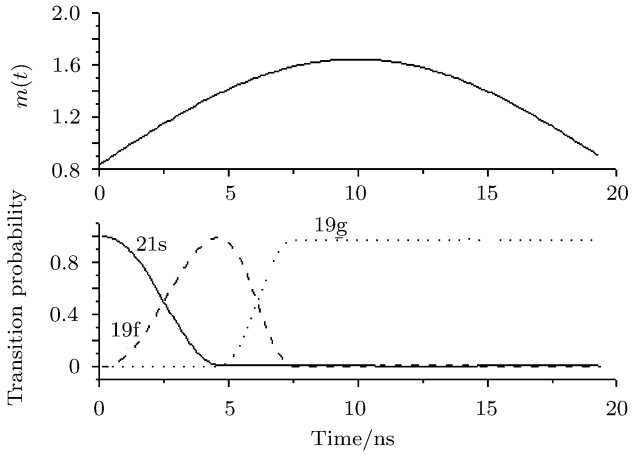


Fig.5. Population transfer (97.6%) between the selected states in three-level-ladder systems using sine pulse: $m(t) = 1 + \sin(\pi t/T)(T = 20$ ns).

For the ladder-type system with our specially designed laser field, 'perfect' population transfer can be achieved with arbitrary laser pulse shape. This can be understood as that the system is in the adiabatic regime. Because the two frequencies of the laser representation correspond to two resonant frequencies between two selected states respectively, while the population transfer to the target state is complete at some moment, the frequency is set to be non-resonant between the two states. Using this scheme, we find that the atom can be excited to any state and trapped in this state successfully. However for different laser pulse shape, the time arrived at the maximum amplitude of population transfer is different, which can induce choosing the suitable laser pulse shape and parameters in the experiment.

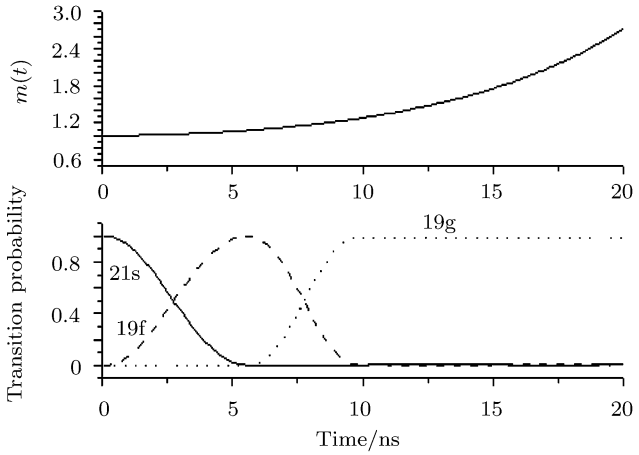


Fig.6. Population transfer (97%) between the selected states in three-level-ladder systems using Gaussian pulse: $m(t) = \exp(t^2/T^2)(T = 20$ ns).

3.3. Three-level-Λ system

For the Λ system, we calculate the population transfer both 21s →19g and 19g→19f with $m(t) = 1$ at first. The value of E_0 and $\omega(t)$ is as follows: when $0 \leq t \leq 8$ ns, E_0= 20 V/cm, $\omega(t) = 33.1023$ GHz; while $8 \leq t \leq 10.6$ ns, E_0= 17.23646 V/cm, $\omega(t) = 25.1013$ GHz. The calculation results are shown in Fig.7. Because $\omega(t)$ of the first laser pulse is the resonant frequency between 21s and 19g states and then tune $\omega(t)$ to be resonant frequency between 19g and 19f states when the population of state 19g reaches the maximum, we observe that the population of state 19f is Rabi oscillation as shown in Fig.7. Then, changing the frequency to be non-resonant between 19f and 19g states when the amplitude of Rabi oscillation reaches maximum, we obtained the results as shown in Fig.8.

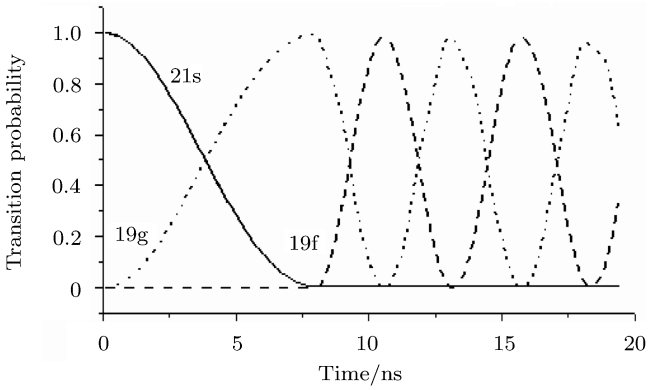


Fig.7. The populations of three states in potassium atoms of there-level-Λ system. The population is first excited to 19g state, and then becomes Rabi oscillation between 19f and 19g states.

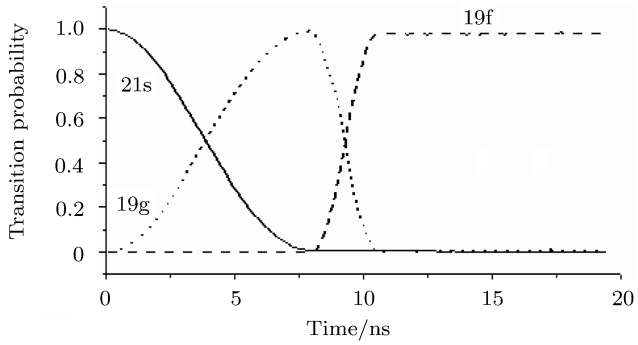


Fig.8. By changing the parameters of laser field, the population is trapped in 19f states eventually.

Then the population transfer is calculated under the condition of the sine pulse shape and Gaussian pulse shape of the laser. For the sine pulse shape, the parameters are as follows: $E_0 = 12.0$ V/cm, when $0 \leq t \leq 8.4$ ns, $\omega(t) = 33.1023$ GHz; when $8.4 \leq t \leq 12.4$ ns, $\omega(t) = 25.1013$ GHz, when $t \geq 12.4$ ns, $\omega(t) = 33.1023$ GHz; for Gaussian pulse shape: $E_0 = 8.5$ V/cm, when $0 \leq t \leq 9.4$ ns, $\omega(t) = 7.995566$ GHz; when $9.4 \leq t \leq 11.9$ ns, $\omega(t) = 25.1013$ GHz. When $t \geq 11.9$ ns, $\omega(t) = 7.995566$ GHz. The calculation results are shown in Fig.9 and Fig.10.

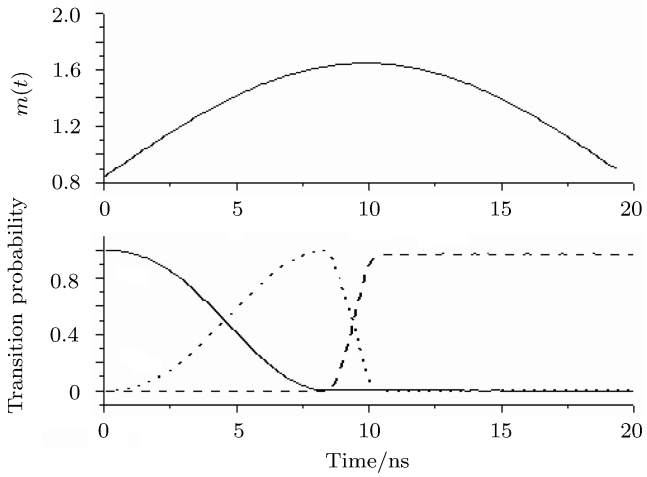


Fig.9. Population transfer (97.%) between the selected states in three-level-Λ system using sine pulse: $m(t) = 1 + \sin(\pi t/T)$,$(T = 20$ ns).

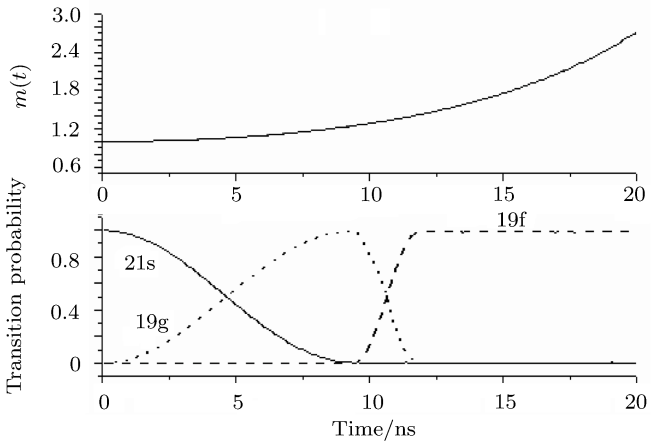


Fig.10. Population transfer (97.%) between the selected states in three-level-Λ systems using Gaussian pulse: $m(t) = \exp(t^2/T^2)(T = 20$ ns).

From Fig.9 and Fig.10, we can see that specially designed laser pulse can lead to the population transfer effectively.

4. Conclusion

The intuition gained from the study of simple systems and interactions like the one presented in this paper may also prove very useful in the more complicated problem of coherent control of a quantum system. The goal in coherent control is to guide the evolution of a system along a particular path to a desired final state. Many different paradigms have been developed to perform such a task, often involving very complicated interactions. Often these globally optimal fields are so complicated that they would be very difficult to calculate. Approaching this problem from the other end by studying the interaction of laser fields with two-level and three-level atom is an important first step toward coherent control of more complicated systems through more complicated interactions.

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