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Original research article

Electromagnetically induced transparency in a spherical quantum dot with hydrogenic impurity in a four level ladder configuration

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ABSTRACT

The present paper analyses the electromagnetically induced transparency (EIT) in the spherical quantum dot with on-center hydrogenic impurity in a four level ladder configuration. The four level ladder configuration is realized by four energy levels of hydrogen impurity: $1S_0$, $2p_{-1}$, $3d_{-2}$, and $4f_{-3}$, together with the probe and two control laser fields which induce σ^- transitions between the given states. Absorption of the probe field as a function of the spherical quantum dot radius and detuning of the probe field is discussed, and comparison of this configuration to the three level ladder configuration is given. Finally, the additional absorption peak that appears in the four level configuration is discussed in detail.

1. Introduction

The study of the optical phenomena based on quantum interference and coherence effects has attracted a lot of attention in recent years. Some of these phenomena are electromagnetically induced transparency (EIT) [1,2], coherent population trapping (CPT) [3,4], lasing without inversion (LWI) [5,6], enhancement of the refractive index [7,8], ultraslow light propagation [9,10], etc. The study of quantum coherence and interference in different systems is therefore important since it has wide application in optical devices, laser spectroscopy, etc.

EIT is a quantum phenomenon, based on quantum interference, for eliminating the effect of a medium on a propagating beam of electromagnetic radiation. Almost all the studies on EIT have been confined to systems in atomic vapors [11–13]. However, developments in modern technology have allowed researchers to fabricate very small semiconductor structures. Among these quantum structures, quantum dots (QDs), in which electrons are confined in all three spatial dimensions, are of particular interest for research in the area of the EIT effect [14,15]. This is because QDs have properties to change energy eigenvalues of the system, their wave functions, and, therefore, their dipole moments and their decay coefficients by changing its dimensions [16]. Therefore, these nanostructures play an important role in nanoelectronic and optoelectronic devices [17,18], since additional confinement can change electrical and optical properties.

Optical properties in low-dimensional structures can also be modified by impurities [19]. Therefore, understanding the effects of impurities on the optical properties of QDs is very important for nanoelectronic and optoelectronic devices and their applications.

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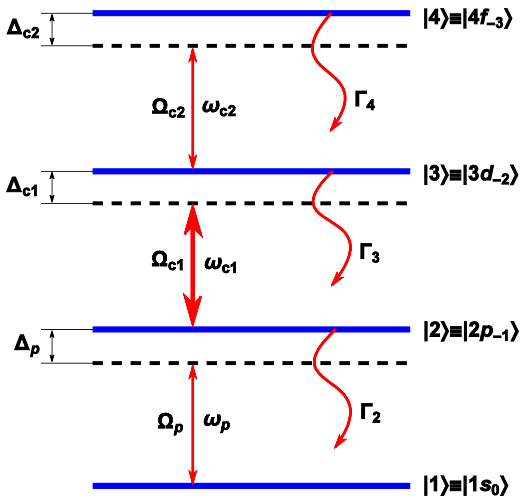

Fig. 1. Schematic energy level diagram of the confined four level hydrogen atom.

To our knowledge, the EIT process in a hydrogen atom confined by a spherical quantum dot (SQD) in a four level ladder configuration has not been investigated so far. The main objective of this paper is to investigate the effect of hydrogenic impurity and SQD radius on the additional absorption peak that appears in the EIT window when two control laser fields are applied. The present paper is organized as follows: the theoretical framework is explained in Section 2, the results and a brief discussion are presented in Section 3, and the conclusion is given in Section 4.

2. Theory

In this paper we used the model of the Hydrogen atom, which is confined in the center of an impenetrable sphere of a radius R_0. This kind of a model can be used for describing the Hydrogen atom which is inside the quantum dot as impurity. The Hamiltonian of this system in atomic units, where distance and energy are measured in effective Bohr radius $a_0^* = 4\pi\varepsilon\hbar^2/(m^*e^2)$ and effective Rydberg $Ry^* = m^*e^4/(4\pi\varepsilon\hbar)^2$, is given by:

$$H = -\frac{1}{2}\Delta + V(r), \tag{1}$$

where the potential energy $V(r)$ is:

$$V(r) = \begin{cases} -\frac{1}{r}, r \le R_0 \\ \infty, r > R_0 \end{cases}. \tag{2}$$

Wave function of the confined Hydrogen atom, since the confining potential is spherically symmetrical, can be written as a product of the radial part $R_{nl}(r)$and spherical harmonics $Y_{lm}(\theta, \phi)$:

$$\Psi_{nlm}(\vec{r}) = C_{nl} R_{nl}(r) Y_{lm}(\theta, \phi), \tag{3}$$

where C_{nl} are the normalization constants. Radial wave function is the solution of the radial Schrodinger equation, and is given by:

$$R_{nl}(r) = r^l e^{-r\sqrt{-2E_{nl}}} F\left(-\frac{1}{\sqrt{-2E_{nl}}} + l + 1, 2l + 2, 2r\sqrt{-2E_{nl}}\right), \tag{4}$$

where F is the confluent hypergeometric (Kummer) function. The values of energies E_{nl} are solutions of Eq. (4) with the boundary condition $r = R_0$, for which wave function is equal to zero.

In this paper we investigate the following four energy levels: $1s_0$, $2p_{-1}$, $3d_{-2}$, and $4f_{-3}$. These levels of the confined hydrogen atom, together with the three laser fields, form a four level ladder configuration, schematically shown in Fig. 1.

The only allowed dipole transitions in this system are those between $1s_0 \leftrightarrow 2p_{-1}$, $2p_{-1} \leftrightarrow 3d_{-2}$ and $3d_{-2} \leftrightarrow 4f_{-3}$. The probe field with the intensity I_p and angular frequency ω_p induces σ^- the transition $1s_0 \leftrightarrow 2p_{-1}$, the control field with intensity I_{c1} and angular frequency ω_{c1} induces the σ^- transition $2p_{-1} \leftrightarrow 3d_{-2}$, and the control field with intensity I_{c2} and angular frequency ω_{c2} induces the σ^- transition $3d_{-2} \leftrightarrow 4f_{-3}$.