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Double electromagnetically induced transparency with nuclei inside a cavity

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ABSTRACT

We propose a double electromagnetically induced transparency (EIT) system of nuclei confined inside a low-finesse cavity excited by a soft X-ray radiation source. The quantitative difference in the density of photon states at the node and antinode of the cavity gives rise to subradiant and superradiant kind of states, respectively. When nuclei ensembles are kept at node, node and antinode in the cavity that sustains X-ray radiation field, the configuration behaves like a four-level system with three degenerate upper levels, of which two are metastable, and thus exhibits the nuclear analog of the optical double EIT phenomenon.

1. Introduction

Recently, in multi-level systems many interesting phenomena such as electromagnetically induced transparency (EIT) and other related effects [1–3] have been extensively studied. The phenomenon of coherent population trapping (CPT) [1] is very closely related with EIT. In a typical EIT system that is composed of three levels (either in ladder, Λ or V-type configuration), two electromagnetic fields are required, where one of the fields is much stronger than the other, so that the quantum interference (QI) is predominantly decided by the stronger field [4]. The EIT can be understood as a process of quantum interference between two discrete states of a medium involving two indistinguishable quantum paths that lead to a common final state and can reduce down the absorption and significantly change the dispersion over a narrow frequency window. In the EIT system, the weak and strong fields are designated as the probe and coupling fields, respectively. In addition to the EIT phenomenon, double EIT occurs when a four-level atomic system is exposed to three laser sources driving three different transitions with one common level [5]. In the situation of double EIT phenomenon the three transitions (having different transition frequencies in general) involved are called the probe, 'coupling' and 'pump' field transitions. In this case, two strong electromagnetic fields, i.e., the coupling and the pump fields, control the medium in determining the absorption, dispersion and thus the propagation of probe field. The double EIT extends EIT to creating two simultaneous transparency windows, one controlled by the coupling field and the other by the pump field [5]. The group velocity of the probe-laser pulse can acquire different values at transparency windows in double EIT systems, which is an important aspect in EIT based quantum memory devices for quantum information processing [6]. These group velocities can be controlled by varying the Rabi frequencies of the coupling and pump laser fields as we will see subsequently. The double EIT has been studied in a four-level optical system in inverted Y-type configuration of its level [5], where several interesting cases of double EIT, e.g., with degenerated EIT windows, non-degenerated EIT windows, etc., under various parametric conditions of the system are discussed. The EIT systems could find applications in the electro-optical devices, controlling group velocity of light, nonlinear optical phenomena, and lasing without inversion [4]. It is the induced atomic coherence in EIT systems that modifies the linear absorption–dispersion aswell as nonlinear properties of the medium [4]. The importance of the double EIT is for the coherent control and enabling long-lived nonlinear interactions between electromagnetic fields (due to slow light propagation in EIT medium), which might facilitate the deterministic all-optical switching to realize multi-qubit quantum gates, multi channel quantum memory devices [6], etc. for quantum information processing. These interesting features of the double EIT phenomenon in four-level optical systems have motivated us to extend the concept of the double EIT in the nuclear regime where X-ray radiation is employed. Such an extension would be useful in realizing multichannel quantum memory devices in nuclear regime using the concept of generalized dark-state polariton of optical domain [6].

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In a recent experiment electromagnetically induced transparency (EIT) was demonstrated using hard X-rays and 14.4 keV nuclear transition of ^{57}Fe isotope which is commonly used in the Mössbauer spectroscopy [7]. This experiment has extended and established the mechanism associated with the 'optical radiation' quantum control to 'X-ray radiation' regime. The success of such experiments goes to the accelerator driven radiation sources such as storage rings and X-rays laser, which provide electromagnetic fields with very high brightness suitable for spectroscopy in the nuclear domain. The conventional EIT system in optical domain involves three-level configuration (with one of the levels being metastable) is quite difficult to realize in the nuclear regime. Also, the properly synchronized two-color X-ray sources required for this purpose are not available. Hence a novel technique of obtaining EIT in nuclear regime was envisaged by proper placement of ^{57}Fe nuclei in the planar cavity suitable for the hard X-ray radiation. In the planar cavity, two layers of ^{57}Fe isotopes are kept at the node and antinode positions of the standing wave pattern sustained in the cavity. When spectral response is determined for such a system, a prominent 'dip' is observed [7], which resembles the EIT dip observed in the optical systems. The appearance of such transparency feature in nuclear regime depends very sensitively on the placement of ^{57}Fe layers inside the cavity. For example, when the placement of such layers is in the sequence of node and antinode, EIT is displayed but when the sequence is other way, e.g., antinode and node then no EIT is observed. Such EIT effect of nuclear regime EIT was theoretically demonstrated also by calculating the reflected amplitude for a grazing incident X-ray radiation. That calculation matched quite well with the experiment [7]. In this work we have theoretically modeled the double EIT phenomenon in nuclear regime by placing three layers of ^{57}Fe isotopes in the planar cavity, first two layers at nodes and third one at antinode of the standing wave pattern sustained in the cavity. The expression of the reflectivity [8] of planar cavity containing three such very thin layers are obtained in powers of nuclear resonant scattering amplitude using transfer matrix approach. Expression for the group velocity is also given. We have also extrapolated the expression to the general multi-EIT system consisting of $(M+1)$ layers, in which first M layers of ^{57}Fe isotopes are kept at nodes and the last one at antinode of the standing wave pattern sustained in the cavity.

The paper is organized as follows. In Section 2, we present our model and its solution followed by results and their discussion in Section 3. We give some concluding remarks in Section 4.

2. The model

In this work we extend the idea of single EIT phenomenon of nuclear regime to the double EIT phenomenon of the nuclear regime. We consider a low finesse cavity and place three layers of ^{57}Fe films at node, node and antinode, respectively. These layers behave like ensembles of nuclei. The distribution (or density) of photon states at node and antinode of the field sustained inside the cavity is considerably different and hence the decay rates of nuclei ensemble situated at node and antinode are also different [7]. When three ensembles of nuclei are kept at node, node and antinode positions then such a configuration behaves as a four-level system having three degenerate upper levels $|2\rangle, |3\rangle, |4\rangle$ and a lower level $|1\rangle$. The upper levels are connected to the lower levels by the interaction generated through the vacuum field of the cavity. Such an interaction is effectively generating two control fields acting on the level $|3\rangle$, though the levels $|2\rangle$ and $|4\rangle$. The levels $|2\rangle$ and $|4\rangle$ behave like metastable states and hence the decay constants of upper states are following the relation $\gamma_2 = \gamma_4 \ll \gamma_3$ as shown in Fig. 1. The system shown in Fig. 1 closely resembles in its functioning as double-Λ (tripod) system. The ensembles at the position of antinode undergo superradiant enhancement of the decay rate (γ_3), while the ones at nodes have the subradiant decay rate (γ_2) equal to the natural linewidth of the transition and $\gamma_2 = \gamma_3/50$ [7]. Such a condition of different decay rates of ensembles placed at nodes and antinodes facilitates the observation of double EIT phenomenon in the nuclear regime as we will explicitly demonstrate in the following.

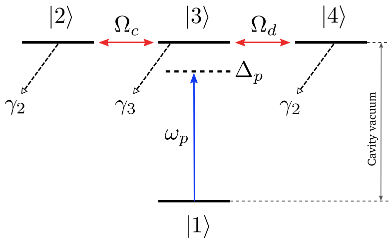

Fig. 1. Schematic diagram of a four-level system exhibiting double-EIT phenomenon in nuclear regime. Three ensembles of ^{57}Fe isotope of iron are kept at nodes (represented by levels $|2\rangle$ and $|4\rangle$) and the antinode (represented by the level $|3\rangle$) of the nuclear cavity with low finesse. All upper states are connected to the ground state by the vacuum field of the cavity. The levels $|2\rangle$ and $|4\rangle$ are metastable in this configuration of the cavity.

The electromagnetic field (say E) at X-ray wavelength enters the cavity at a grazing incidence angle ϕ (see Fig. 2). In experimental conditions [7], this angle was 3.5 mrad (0.2°) and hence the magnitude of such field is $E\cos(0.2) \approx E$. The field entering the cavity at grazing incidence is responsible for the standing wave formation inside the cavity due to the superposition of two beams (i.e., the incidence and reflected). This superposition facilitates the making of nodes and antinodes configuration of field inside the cavity, which is the basis of observing EIT in the nuclear domain. There is another component of field (the traveling field) given by $E\sin(0.2) \approx 10^{-3}E$ also travels down the cavity straight. Since the magnitude of the traveling field is comparatively so small that it does not hamper the formation of the antinodes and nodes (key factors for observing nuclear EIT) in the cavity due to the grazing incidence field. On the other hand, when the angle ϕ is large enough such that the grazing incidence condition is not fulfilled, then the magnitude $E\sin(\phi)$ of the traveling field cannot be neglected. The traveling field in such situation will make multiple reflections with appreciable amplitudes, which may hamper with the standing wave formation due to the grazing incidence field this time. Under this condition, observation of EIT could be deteriorated. The quantitative estimates of such deterioration are under consideration in a separate work [9] to be published in near future.

Next, we derive the expression of the reflectivity [8] of planar cavity containing three very thin layers of the ^{57}Fe material placed at the node, node, and antinode of the cavity. We further assume that the individual thicknesses of the ^{57}Fe layers are much smaller than the total thickness of the system so that perturbation theory can be applied to calculate reflectivity in powers of nuclear resonant scattering amplitude (f_n). The layers having thicknesses t_1, t_2, and t_3 are located in the z-direction at coordinates z_1, z_2, and z_3, respectively, in the planar waveguide (Fig. 2). We follow the transfer matrix theory [7] to obtain the transmitted amplitude (designated by the positive sign '+') and reflected amplitude (designated by the negative sign '−') at a depth z, which we call $\mathbf{B}(z)$ such that $\mathbf{B}(z) \equiv (B_+(z), B_-(z))$. The field at the surface, i.e., at $z=0$ is given by $\mathbf{B}(0) \equiv (B_+(0), B_-(0))$. Our aim is to calculate $B_-(0)$, which is the amplitude reflected back at the surface ($z=0$) after undergoing the process of scattering in the layer system. For this purpose we first find out the field amplitude at $z=W$, which is the depth of the total system. It is straightforward to write [7,8]