Coherent transients with a single photon

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Reversible coherent transients induced by a single photon in an ensemble of resonant particles are considered. It can be shown that a phase shift of a single photon wave packet produces its re-emission by these particles. As an example, the resonant interaction of a single gamma-photon with Mössbauer nuclei is theoretically analyzed. This example has interesting applications in such areas as information transmission and measuring of sub-angstrom vibrations of thin films for creating of sub-angstrom etalon displacements, which can be used for sensor calibration. We show that coherent transients that are governed by the time evolution of a population of nuclear excited states can be detected not only in the transmission of photons through resonant absorbers, but also directly in the time evolution of a population of nuclear excited states. These states experience radiative decay and also emit conversion electrons. The detection of conversion electrons provides information about the excited state population of nuclei located nearby the surface of the radiation incidence on the absorber. This is because of short mean free path (or escape depth) of these electrons in the bulk.

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Coherent gamma-optics is quite fruitful for the development of ideas how to work with single photons. This is because of availability of single photon sources (for example, radioactive ^{57}Co) emitting gamma photons with long coherence time, resonant absorbers with narrow absorption line (for example, ^{57}Fe), and conventional equipment for time-domain Mössbauer spectroscopy. In our paper we consider reversible absorption of single gamma-photon by a thin layer of resonant particles. Our results can be applied for the development of a technique of information transmission by a random flow of single photons and creating of sub-angstrom etalon displacements, which can be used for sensor calibration.

Recently, we reported information transmission by a random flow of gamma-photons [1]. The method is based on generation of controlled gamma-ray bursts, which can be seen if information coding and detection are synchronized. The information is imprinted into a stochastic flow of gamma-photons by transmitting through a resonant absorber experiencing fast displacements with respect to the radiation source. The absorber at rest simply reduces the intensity of the radiation field. If the absorber is displaced fast on a half wavelength, the incident field and resonantly forward-scattered field interfere constructively immediately after displacement. This interference produces the radiation pulse known as gamma-echo [2]. Fast displacements are produced by piezoelectric transducer, which is fed by voltage pulses of rectangular shape. Leading and trailing edges of these voltage pulses produce gamma-bursts.

In gamma-echo experiments, time of formation of the excited state nucleus ^{57}Fe in the source and emission of 14.4 keV photon, which is resonant for ^{57}Fe in the absorber, is announced by detection of 122 keV precursor photon emitted by ^{57}Co in a cascade decay. To clearly observe a gamma-burst, a voltage pulse must be applied some time after the detection of the 122 keV precursor photon. This time interval is necessary for a formation of the field resonantly scattered in a forward direction.

If one applies a rectangular voltage pulse, repeated periodically, and synchronizes detection of gamma-photons with this period, then the gamma-bursts can be made visible even without synchronization with detection of the precursor photon [3–5]. This is the essence of the method of information transmission using a random flow of gamma-photons [1]. Further development and improvement of the transmission rate of this method need detailed knowledge and control of the parameters of the absorber displacements. Control and calibration of the parameters of ultra-small (less than angstrom)

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displacements of thin films is also of current interest in the field of ultra-precision machining, high-precision displacement measurement, and sensor calibration [6, 7].

Gamma-echo contains the necessary information of the displacement parameters. However, sequential multiscattering of a photon on resonant nuclei in the absorber complicates the analysis. This is because even physically thin absorber has noticeable effective thickness, which attenuates the field. This attenuation is necessary for the observation of pronounced gamma-echo since the presence of many resonant particles on the way of photon to a detector allows development of noticeable antiphase field, coherently scattered by the resonant particles in a forward direction. A fast π-phase shift of the incident field brings it in phase with the previously scattered field, creating the gamma-burst.

In this paper we propose another method to determine the displacement parameters directly, excluding the influence of thickness effect. This method allows to trace the state evolution of a single nucleus, avoiding the complications introduced by the phenomena of photon propagation in a "thick" resonant medium. We show that the π-phase shift of the incident field reverses the process of photon absorption to re-emission. This gives a new interpretation of gamma-burst.

The method is based on detection of conversion electrons emitted by excited state nuclei in the absorber. These nuclei decay by emission of 14.4 keV photon (radiative decay) and by emission of conversion electron (non-radiative decay). Because of short mean free path of conversion electrons in solids, these electrons are emitted predominantly by the surface nuclei in the absorber. Therefore, photon multiscattering processes are excluded.

In this paper, we analyze the population evolution of an excited state nucleus in the absorber when the phase of gamma-photon changes due to fast stepwise displacements. We consider the ground and excited states of absorber nucleus as a two-level system [8]. Its time evolution can be described by pseudospin 1/2 [9]. This spin is directed downwords if nucleus is in the ground state or upwards if it is in an excited state. The evolution of this pseudospin with components u, v, and w is shown in Fig. 1. These components, $w = \rho_{ee} - \rho_{gg}$, $u + iv = 2\rho_{ge} \exp(-i\omega_s t)$, are the combinations of the density matrix elements ρ_{ge}, ρ_{ee}, ρ_{gg}, describing the evolution of nuclei in the ground g and excited e states.

Before excitation, nucleus is in the ground state, which corresponds to the vector $\mathbf{S}_0$, shown in Fig. 1. If at time t_0 the electromagnetic field (shown by the vector $\boldsymbol{\chi}$) is turned on, the vector $\mathbf{S}_0$ rotates counterclockwise in the $w-v$ plane. As a result, the population

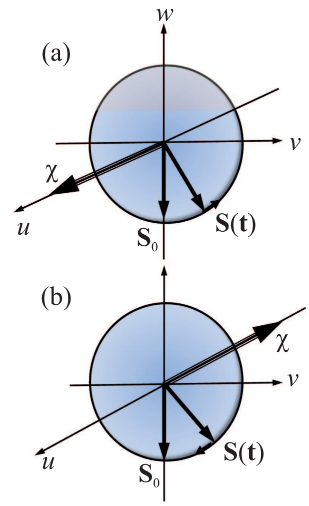

Fig. 1. (Color online) (a) – Evolution of pseudospin $\mathbf{S(t)}$ with components u, v, and w subject to interaction with the radiation field $\boldsymbol{\chi}$. (b) – Evolution of pseodospin after abrupt phase shift of the field by π. Vector $\mathbf{S}_0$ depicts pseudospin position in the Bloch sphere before interaction with the field

of the excited state nuclei increases, and population of the ground state decreases. The position of the pseudospin at time t_1 is shown by the vector $\mathbf{S(t)}$. At this moment, the vector $\boldsymbol{\chi}$ changes its direction to the opposite, and the vector $\mathbf{S(t)}$ begins to rotate in the opposite direction (clockwise). Then the population of the excited state decreases and the energy accumulated during nuclear excitation in the time interval (t_0, t_1) is released. This results in the radiation pulse emission seen as gamma-burst.

Two types of experiments are considered. In the first scheme, time evolution of excited state population is proposed to be measured if the phase change is synchronized with the time of formation of an excited state nucleus in the source. This time is announced by detection of a 122 keV precursor photon, which starts the clock in data accusation module, collecting conversion electron counts, and indicates time when to begin displacement experiment. Detection of a conversion electron stops the clock in data accusation module. By collecting many counts, it is possible to reconstruct time evolution of excited state nuclei in the absorber experiencing fast displacements.

In the second type of experiments, it is possible to collect conversion electron counts without synchronization with the time of formation of an 14.4 keV excited state nucleus in the source. In this case, the time evolution of the population of excited state nuclei in the absorber is averaged over the time of emission of a 14.4 keV photon by the source. The data acquisition module is synchronized with the time of mechanical displacements of the absorber to find the time evolution of the population of the excited state nuclei after displacement. The results of such an experiment [4] are compared with our theoretical model. We also analyze the case when the time interval of two successive displacements of the absorber is varied to understand how close they could be to distinguish clearly the displacement-induced gamma-radiation bursts. This information can help increase the rate of the information transmission with gamma photons [1].

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Conflict of interest. The authors of this work declare that they have no conflicts of interest.

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