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**ELEMENTS OF QUANTUM COMPUTER THEORY: A
MODEL FOR THE FORMATION OF A Q-BIT STATE**

Abstract. In recent years, there has been considerable interest in the possibility of creating quantum computers that use systems—each of which has an $SU(2)$ space - instead of electronic cells with a dichotomous state spectrum (0, 1). This paper proposes a model intended to serve as an example of the procedure for preparing an atom and a field for a specific, given quantum state. The proposed methodology is aimed at obtaining results for the development of theory and the practical creation of quantum computers.

Keywords: quantum computer, atom, field, laser, model, q- bit, state

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**ЕЛЕМЕНТИ ТЕОРІЇ КВАНТОВИХ КОМП'ЮТЕРІВ:
МОДЕЛЬ ФОРМУВАННЯ СТАНУ Q-БІТА**

Анотація. В останні роки значний інтерес викликає можливість створення квантових комп'ютерів, у яких замість електронних комірок із дихотомічним спектром станів (0, 1) використовуються системи, кожна з яких має простір $SU(2)$. У роботі запропоновано модель, призначену як приклад процедури підготовки атома та поля до певного заданого квантового стану. Запропонована методика спрямована на отримання результатів для розвитку теорії та практичного створення квантових комп'ютерів.

Ключові слова: квантовий комп'ютер, атом, поле, лазер, модель, q-біт, стан

Introduction. Problem Statement. In recent years, there has been considerable interest in the possibility of creating quantum computers (QC), in which systems with $SU(2)$ space (such as correlated two-level atoms or photons) play the role of electronic

cells with a dichotomous state spectrum (0,1) [1]. Modern techniques allow for the fairly reliable preparation of specific states of atoms and fields. This paper proposes a model intended to serve as an example of a procedure for preparing an atom and a field in a specific, given quantum state. The ability to manipulate wave functions will open up new possibilities for experimentally verifying practical predictions of quantum theory regarding the interaction of a field with matter. The proposed technique is aimed at obtaining results for the development of the theory and the practical creation of quantum circuits.

Formation of a q-bit state. When describing the interaction of atoms with resonant monochromatic radiation, it is sometimes sufficient to consider only two non-degenerate energy levels of the atom. In this case, the free state of the atom can be represented as a superposition of two basis vectors: $|\psi\rangle = \alpha|g\rangle + \beta|e\rangle$ (where the letters g and e denote the lower and upper levels, respectively). Thus, the ground state of a two-level atom is given by a pair of complex numbers (α, β) . If we take into account the standardization condition $|\alpha|^2 + |\beta|^2 = 1$, and if we also neglect the total phase α and β , then the state is determined by two parameters of the substance (for example, the coordinates of points (θ, ϕ) on the Bloch sphere [2]).

The polarization state of a classical monochromatic wave or photon can be represented on a corresponding Poincaré sphere [3]. A single-mode field in a resonator (with a specific polarization) interacting with a two-level atom can be in a superposition of the vacuum state and the single-photon state. The space of the resonator in question has the same structure: $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$. The state space of particles with spin 1/2 has a similar geometry. In terms of group theory, such a space is called an SU(2) space [1].

The procedure for forming a q-bit state is as follows. All qubit cells must be in a single pure entangled state Ψ . Such a device leads to a significant increase in the speed of solving problems in certain classes. The information contained in the numbers (α, β) or (θ, ϕ) is specifically called a q-bit (qubit). When an atom interacts with a single-mode field in a resonator, a reverse exchange of q-bits may occur

$$|\Psi\rangle = (\alpha|g\rangle + \beta|e\rangle)|0\rangle \rightarrow |\Psi'\rangle = |g\rangle(\alpha|0\rangle + \beta|1\rangle) \quad (1)$$

The process and the subsequent back transfer of q-bits from the field of another atom were studied in [4]. The interaction of two atoms via a field also made it possible to experimentally produce two atoms in an entangled EPR state [5]:

$$|e_1, g_2, 0\rangle \rightarrow \frac{(|e_1, 0\rangle + |g_1, 0\rangle)|g_2\rangle}{\sqrt{2}} \rightarrow \frac{(|e_1, g_2\rangle + |e_2, g_1\rangle)|0\rangle}{\sqrt{2}}. \quad (2)$$

In quantum teleportation, a q-bit is irreversibly transferred from one photon to another.

Modern technologies allow a single atom to be confined within a limited space (a magneto-optical trap) and cooled to extremely low temperatures on the order of 10^{-7} K. Under these conditions, the atom transitions to the ground state $|g\rangle$. Suppose that at time t_0 , the atom is exposed to a short-duration (τ) laser pulse with a specific amplitude (a π -pulse). Intense laser radiation can be treated classically with high accuracy. The laser frequency equals the transition frequency $\omega_e = \frac{(E_e - E_g)}{\hbar}$ between the ground state $|g\rangle$ and one of the excited states $|e\rangle$ of the atom. According to the theory, when exposed to a laser pulse, the atom transitions to a specified state $|\psi\rangle = \alpha|g\rangle + \beta|e\rangle$, where

the coefficients α and β determine the phase of the optical oscillations and the area of the laser pulse (the product of the amplitude E_0 and the duration τ). This method is used in modern research [4,5]. Subsequently, the state evolves according to the Schrödinger equation: $|\psi_t\rangle = \alpha|g\rangle + \beta|e\rangle \exp(-i\omega_e t)$.

To account for unexpected fluctuations in the laser's amplitude and phase, the state of the atomic ensemble during repeated experiments was described by a mixed state. It should be emphasized that during the described procedure, the properties of the quantum object are not measured; that is, the preparations do not involve measurement, as is traditionally done. The main assumption is a classical description of the laser field, which acts as a given external force and accounts for the relaxation that brings the atom to the ground state $|g\rangle$. During the measurement process, at the preparation stage, a boundary between the classical and quantum descriptions is established based on general physical pictures. This procedure is based on the adequacy of heuristic semi-classical models, which were developed based on the results of fairly successful experiments.

The interaction of atoms with unconstrained (vacuum) field modes, which are allowed over short time intervals, was taken into account. This interaction causes spontaneous photon emission (an exponential wave packet with an average frequency ω_e and duration $\tau_e = 1/w_{ge}$, which determines the probability of a spontaneous transition per unit time w_{ge}). A point on the Bloch sphere (corresponding to the state of the atom) will move in a spiral from the north pole to the south pole. After some time ($t \gg \tau_e$), the atom will, with high probability, be at the south pole in the ground state, and the field will be in the single-photon state $|1\rangle$.

In this way, the proposed model serves as an example of a procedure for preparing an atom and a field in a specific, predetermined state. Thus, modern techniques allow for the fairly reliable preparation of specific states of atoms and fields. This ability to manipulate wave functions is widely used for the experimental verification of practical predictions of quantum information theory regarding the interaction of a field with matter [6].

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