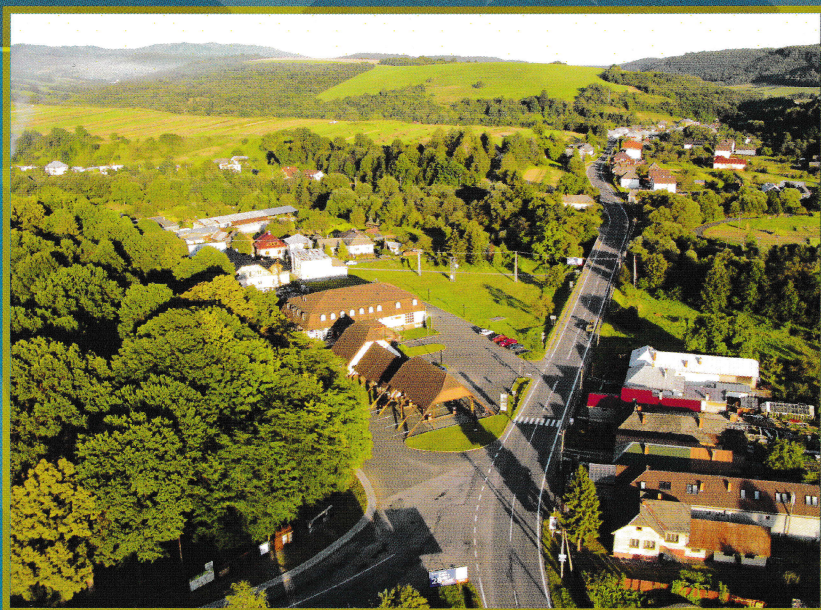


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Quantum Teleportation and Resonant Transmission of Quantum Information between Two-Level Atoms Located at Large Distance from Each Other

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Abstract

The feasibility of resonance transfer of quantum information from one two-level atom to another that is at an arbitrary distance from the former one has been proved. Symmetric and antisymmetric combinations of the wave functions of individual atoms are considered. When taking into account the interatomic dipole-dipole interaction, a certain energy corresponds to each wave function. A solution has been found to a system of equations for the amplitudes of the probability that a resonance photon will be absorbed by one of the system atoms, and it has been shown that the interaction of the system with actual photons has the result that the wave function of the final state of the system can be represented as a linear combination of the functions $\langle 00|$, $\langle 0n|$, and $\langle n0|$ corresponding to the ground and excited states of individual atoms. The amplitude of the probability of each of these states depends on the interatomic distance and on the parameters of the action of actual photons on atoms. Three types of solution to the system of equations have been investigated for the resonance and nonresonance absorption of photons and different interatomic distances. It has been shown that when atoms are at an infinite distance from one another, so that there is no dipole-dipole interaction of atoms, quantum information can be transferred from one atom to another with a characteristic time considerably shorter than the time it takes for a photon to cover the interatomic distance. This effect is referred to as the effect of quantum teleportation in a system of resonance atoms.

Introduction

The unit of quantum information (quantum bit or qubit) is a superposition of two base functions of a quantum system [1]. A method for writing quantum information on an individual double-level atom of a system taking a region whose linear dimensions are substantially smaller than the wavelength of photons has

been proposed, where intense quasi-resonance laser radiation is used and the incidence angle of the external radiation on the system is varied [2]–[4]. Of great importance in this method of writing and reading information is resonance transfer of quantum information from one atom to another. On the other hand, transfer of quantum information for arbitrary distances plays an important role in creating quantum communication systems. In this paper, we propose a unified way of describing resonance transfer of quantum information for arbitrary distances, including the effect of quantum teleportation. Quantum teleportation was discovered experimentally [5] with the use of a three-photon scheme for transferring quantum information from one observer to another taking into account two types of polarization of photons. Other schemes of quantum teleportation have also been proposed, for instance, those using a system of three electrons [6] or three atomic beams of two-level atoms [7]. The schemes of quantum teleportation described in [5]–[7] are, in fact, based on the superposition principle for nonlocal quantum systems. In this case, the effect of quantum teleportation does not come into conflict with the principle of relativity since not energy, but information, which acquires an additional sense in quantum processes as compared to the information in classical systems, is transferred instantaneously. In this paper, it is shown that the information about two possible states of atoms can be transferred from atom to atom within a short time interval. For this case, the value of this interval depending on the type of interatomic interaction is calculated. In a system of two identical interacting atoms, absorption (emission) of actual photons is nonlocal in character, namely, the event of disappearance (birth) of a photon may take place at the site of location of one atom, while the quantum transition will occur between the states of the other atom. The classical and quantum methods for information transfer with corresponding characteristic times are also considered.

Energy of the resonant interaction of atoms located at arbitrary distances

Let us write the operator of electric dipole-dipole interaction of two electrons located at an arbitrarily large distance from each other, near different nuclei [8, 9]:

$$\hat{V}_{dip}^{(\pm)} = \exp\left(\frac{i}{c}\omega_0 R\right) \left\{ \frac{\vec{d}_1 \vec{d}_2 - 3(\vec{n}_R \vec{d}_1)(\vec{n}_R \vec{d}_2)}{R^3} \pm \frac{e}{2mc} \left[\frac{\vec{d}_1 \hat{p}_2 - 3(\vec{n}_R \vec{d}_1)(\vec{n}_R \hat{p}_2)}{R^2} - \frac{\vec{d}_2 \hat{p}_1 - 3(\vec{n}_R \vec{d}_2)(\vec{n}_R \hat{p}_1)}{R^2} \right] - \frac{e^2}{m^2 c^2} \frac{\hat{p}_1 \hat{p}_2 - 3(\vec{n}_R \hat{p}_1)(\vec{n}_R \hat{p}_2)}{R} \right\}, \quad (1)$$

where $\vec{n}_R = \vec{R}/R$, $\omega_0 \equiv \omega_{n0} = (E_n - E_0)/\hbar$ is the resonance frequency in the spectrum of the atoms, $\vec{d}_1 = e\vec{r}_1$ and $\vec{d}_2 = e\vec{r}_2$ are the operators of the electric dipole moments of single-electron atoms, \vec{p}_1 and \vec{p}_2 are the operators of the momenta of the first and the second atomic electron, respectively.

For the system of two interacting atoms having one electron, the Hamiltonian \hat{H} can be represented in the form of sum of Hamiltonians of isolated atoms, $\hat{H}_0 =$

$\hat{H}_1(\vec{r}_1) + \hat{H}_2(\vec{r}_2)$, and operator of electric dipole-dipole interaction between them, $\hat{V}_{\text{äcd}}^{(\pm)}$:

$$\hat{H} = \hat{H}_0 + \hat{V}_{\text{dip}}^{(\pm)} = \hat{H}_1(\vec{r}_1) + \hat{H}_2(\vec{r}_2) + \hat{V}_{\text{dip}}^{(\pm)}(\vec{r}_1, \vec{r}_2; R). \quad (2)$$

Let $E_{n_1 n_2} = E_{n_1} + E_{n_2}$ and $|n_1 n_2\rangle$ are the eigenvalue and eigenfunction of "unperturbed" operator of energy $\hat{H}_0 = \hat{H}_1 + \hat{H}_2$ without interatomic interaction, respectively. The unperturbed wave function of the initial state of two atoms has the form

$$|00\rangle = \varphi_0(1)\varphi_0(2) \exp(-iE_0 t_1/\hbar) \exp(-iE_0 t_2/\hbar) \equiv \tilde{\varphi}_0(1)\tilde{\varphi}_0(2). \quad (3)$$

Here E_0 is the energy of the initial states of the first and second atoms, the indices 1 and 2 correspond to the coordinates and times for the first and the second atom, respectively. For atoms having no constant dipole moment in the first order of perturbation theory, the energy correction is zero, i.e., $\langle 00|\hat{V}_{\text{äcd}}^{(\pm)}|00\rangle = 0$. The interaction between the atoms distorts the wave functions of the atomic states, and the disturbed wave function for a system of two atoms in the ground state has the form [10, 1]):

$$\Psi_0(1)\Psi_0(2) = \tilde{\varphi}_0(1)\tilde{\varphi}_0(2) + \sum_{n_1 n_2} \frac{\langle \tilde{\varphi}_{n_1}(1)\tilde{\varphi}_{n_2}(2)|\hat{V}_{\text{dip}}^{(\pm)}|\tilde{\varphi}_0(1)\tilde{\varphi}_0(2)\rangle}{2E_0 - E_{n_1} - E_{n_2}} \tilde{\varphi}_{n_1}(1)\tilde{\varphi}_{n_2}(2), \quad (4)$$

where the indices n_1 and n_2 correspond to intermediate states of the atoms. We consider the state $\Psi_0(1)\Psi_0(2)$ as initial state of atoms interacting with field of real photons.

Let the final state $|n0\rangle$ of two resonant atoms corresponds to the excited state $|n\rangle$ of atom A(1) with wave function $\tilde{\varphi}_n(1) = \varphi_n(1) \exp(-iE_n t_1/\hbar)$ and energy E_n and ground state $|0\rangle$ of atom A(2) with wave function $\tilde{\varphi}_0(2) = \varphi_0(2) \exp(-iE_0 t_2/\hbar)$ and energy E_0 .

In the zeroth approximation, to the stationary state of the system corresponds to two wave functions:

$$\Phi_s(1, 2) = \frac{1}{\sqrt{2}} [\tilde{\varphi}_n(1)\tilde{\varphi}_0(2) + \tilde{\varphi}_0(1)\tilde{\varphi}_n(2)], \quad (5)$$

$$\Phi_a(1, 2) = \frac{1}{\sqrt{2}} [\tilde{\varphi}_n(1)\tilde{\varphi}_0(2) - \tilde{\varphi}_0(1)\tilde{\varphi}_n(2)]. \quad (6)$$

In order to obtain corrections to the energy of symmetrical (5) and antisymmetrical (6) states of system of two resonant atoms in the first order of perturbation theory one has calculate the mean value of the perturbation operator $\hat{V}_{\text{dip}}^{(\pm)}$ (1) in these states, i.e.,

$$\Delta E_s = \langle \Phi_s|\hat{V}_{\text{dip}}^{(\pm)}|\Phi_s\rangle, \quad \Delta E_a = \langle \Phi_a|\hat{V}_{\text{dip}}^{(\pm)}|\Phi_a\rangle. \quad (7)$$

Substituting the expressions (1), (5) and (6) into the matrix elements (7) we obtain that

$$\begin{aligned} \Delta E_s(R) = -\Delta E_a(R) = \omega_0^3 e^{i\omega_0 R/c} |\langle n|\vec{d}|0\rangle|^2 \times \\ \times \left[\left(\frac{1}{\omega_0^3 R^3} - \frac{i}{\omega_0^2 R^2} \right) \Phi(1, 2) - \frac{\Phi'(1, 2)}{c^2 \omega_0 R} \right] \equiv \Delta E_{AA}(R). \end{aligned} \quad (8)$$

Here

$$\begin{aligned}\Phi(1, 2) &\equiv \cos \theta_1^x \cos \theta_2^x + \cos \theta_1^y \cos \theta_2^y - 2 \cos \theta_1^z \cos \theta_2^z, \\ \Phi'(1, 2) &\equiv \cos \theta_1^x \cos \theta_2^x + \cos \theta_1^y \cos \theta_2^y\end{aligned}$$

are the geometric factors, θ_i^x , θ_i^y , θ_i^z ($i = 1, 2$) are the angles between one of corresponding axes and the direction of dipole transition in i -th atom $A(i)$.

Note that the quantity ΔE_s (ΔE_a) is complex shift of energy E_s (E_a) of symmetrical (antisymmetrical) state Φ_s (Φ_a) of atoms:

$$\Delta E_s = \delta E_s - \frac{i}{2} \hbar \gamma_s, \quad \Delta E_a = \delta E_a - \frac{i}{2} \hbar \gamma_a. \quad (9)$$

First-order corrections to the energy $E_n + E_0$ of states (5) and (6) gives only real parts δE_s and δE_a of complex shifts:

$$\delta E_{s,a}(R) = \pm \text{Re} \Delta E_{AA}(R) = \pm \frac{e^2 \hbar f_{n0}}{2m\omega_0} F(1, 2; R). \quad (10)$$

Here

$$F(1, 2; R) = \left[\frac{\Phi(1, 2)}{R^3} - \frac{\omega_0^2 \Phi'(1, 2)}{c^2 R} \right] \cos \left(\frac{\omega_0 R}{c} \right) + \frac{\omega_0 \Phi(1, 2)}{cR^2} \sin \left(\frac{\omega_0 R}{c} \right), \quad (11)$$

f_{n0} are observable strengths of oscillators of corresponding transitions.

The expressions for δE_s and δE_a can be simplified at $\omega_0 R/c \rightarrow 0$, i.e., when size of two-atomic quantum system is much smaller than characteristic wave length $\lambda_0 = 2\pi c/\omega_0$ in spectrum of interacting atoms ($R \ll \lambda_0$). In this case one can neglect retardation of dipole-dipole interaction of atoms, that makes it possible to substitute $\cos(\omega_0 R/c) = 1$, $\sin(\omega_0 R/c) \approx \omega_0 R/c$ in the expression (11) for F and to omit terms containing velocity of light c . Then for δE_s and δE_a we obtain

$$\delta E'_{s,a} = \pm \frac{e^2}{R^3} |\langle n | \vec{r} | 0 \rangle|^2 \Phi(1, 2). \quad (12)$$

As one would expect, this expression coincides with the known formula [10] for the energy of resonant exchange of excitations between two neutral atoms located closely one from other.

Therefore, we see that at account of dipole-dipole interatomic interaction (1) symmetrical and antisymmetrical states of atoms are characterized by the energies

$$E_s = E_n + E_0 + \delta E_s = E_n + E_0 + \frac{e^2 \hbar f_{n0}}{2m\omega_0} F(1, 2; R), \quad (13)$$

$$E_a = E_n + E_0 + \delta E_a = E_n + E_0 - \frac{e^2 \hbar f_{n0}}{2m\omega_0} F(1, 2; R). \quad (14)$$

and wave functions

$$\Psi_s = \Phi_s \exp(-i\delta E_s t_1/\hbar), \quad \Psi_a = \Phi_a \exp(-i\delta E_a t_1/\hbar), \quad (15)$$

where t_1 is the local time for the atomic pair associated with the position of the atom $A(1)$.

It is apparent that states (15) are entangled states of a pair of interacting atoms because in these states separate atom-qubit has not certain energy.

In the first order of perturbation theory the contribution of dipole interaction in complete width Γ_s (Γ_a) is determined by imaginary part γ_s (γ_a) of doubled complex shift ΔE_s (ΔE_a):

$$\gamma_s(R) = -\gamma_a(R) = -2\text{Im}\Delta E_{AA}(R) = -\frac{3}{2}\gamma_0 c^3 \tilde{F}(1, 2; R), \quad (16)$$

where

$$\tilde{F}(1, 2; R) = \left[\frac{\Phi(1, 2)}{\omega_0^3 R^3} - \frac{\Phi'(1, 2)}{c^2 \omega_0 R} \right] \sin\left(\frac{\omega_0 R}{c}\right) - \frac{\Phi(1, 2)}{c \omega_0^2 R^2} \cos\left(\frac{\omega_0 R}{c}\right), \quad (17)$$

γ_0 is the radiation rate of an excited state E_n of the isolated atom.

The general expression (16) for γ_s and γ_a can be essentially simplified in the limit cases of "large" ($R \gg \lambda_0$) and "small" ($a < R \ll \lambda_0$) interatomic distances. For example, when $\omega_0 R/c \ll 1$ and orientations of dipole transition are identical in the both atoms ($\theta_1^x = \theta_2^x$, $\theta_1^y = \theta_2^y$, $\theta_1^z = \theta_2^z$) formula (17) becomes

$$\gamma_s(R) = -\gamma_a(R) = \gamma_0 \left[1 + O\left(\frac{\omega_0^2 R^2}{c^2}\right) \right]. \quad (18)$$

The complete widths of symmetrical and antisymmetrical states are of the form:

$$\Gamma_s = \gamma_0 + \gamma_s \approx 2\gamma_0, \quad \Gamma_a = \gamma_0 + \gamma_a \approx O\left(\frac{\omega_0^2 R^2}{c^2}\right), \quad (19)$$

We can see that under the condition $R \ll \lambda_0$ the retarded interaction of atoms in the symmetrical state Ψ_s (15) leads to doubling of natural width of atomic levels. For antisymmetrical state the widths γ_a and γ_0 compensate each other almost completely, and the complete width Γ_a is small when compare with γ_0 . It means that when $R \ll \lambda_0$ retarded interaction of atoms completely suppresses radiation decay of excited states of atoms. This property of mutual influence of closely located atoms was interpreted in [12] as near-field effect.

In paper [13] the near-field effect was proposed as a basis of writing the quantum information on separate two-level atoms of two-qubit quantum computer by means of intensive quasiresonant radiation at a modification of an angle of incidence of external wave. Reading of the quantum information (after calculations) can be performed by means of weakly intensive probe radiation using solutions of equations system for dipole oscillators obtained in [12].

Quantum teleportation and resonant transmission of quantum information between two atom-qubits

Let us assume that at the initial point in time $t_1 = 0$ the system of two atoms under consideration is in the state $\Psi_m^{(0)} = \Psi_0(1)\Psi_0(2)$ (see (4)). Let us consider

the quantum transition $\Psi_m^{(0)} \rightarrow \Psi_n^{(0)} = \Psi_{s(a)}$, where the wave functions $\Psi_{s(a)}$ are given by formulas (15). We define the transition energy for this case as

$$E_m^{(0)} - E_n^{(0)} = E_0 - E_n \mp \Delta E_s = -\hbar(\omega + \Delta), \quad (20)$$

where the upper sign corresponds to the symmetric state Ψ_s of the atomic pair, while the lower sign refers to its antisymmetric state Ψ_a , ω is the frequency of a real photon, Δ is the resonance off-tuning. Let us assume that the quantum transition $\Psi_m^{(0)} \rightarrow \Psi_{s(a)}$ corresponds to the event of annihilation of the photon. With that, we shall consider the transitions $\Psi_m^{(0)} \rightarrow \Psi_a$ and $\Psi_m^{(0)} \rightarrow \Psi_s$ separately from one another. For the symmetric channel $\Psi_m^{(0)} \rightarrow \Psi_s$ we have the following system of equations which determine the probability amplitudes a_m and a_n with the proviso that $\Gamma_s t_1 \rightarrow 0$:

$$\left. \begin{aligned} i\hbar \frac{da_m}{dt_1} &= F_{mn}^* \exp[i(\omega_{mn} + \omega)t_1] a_n = F_{mn}^* \exp(i\varepsilon_+ t_1) a_n, \\ i\hbar \frac{da_n}{dt_1} &= F_{mn}^* \exp(-i\varepsilon_+ t_1) a_m, \end{aligned} \right\} \quad (21)$$

where $\varepsilon_+ = (\delta E_s - \hbar\Delta)/\hbar$; the matrix element of the transition is given by

$$F_{mn} = -\frac{i}{c} \omega_0 \vec{A}_0 \vec{d}'_{n0} \exp(i\vec{k}\vec{R}), \quad (22)$$

\vec{A}_0 is the amplitude of the vector potential, \vec{k} is the wave vector of the real photon which is absorbed at the location of the second atom with the radius vector \vec{R} . The matrix element \vec{d}'_{n0} in (22) takes into account all terms of the function (4) of the initial state. The system of equations (21) corresponds to the two-level approximation for a system of atoms, such that the most significant contribution is from those terms of the Schrödinger wave equation in which the dependence on time is determined by a low frequency ($\omega_0 - \omega$). A similar system of equations will also take place for the antisymmetric channel if in (21) we replace ε_+ with ε_- , defined as $\varepsilon_- = -(\delta E_s + \hbar\Delta)/\hbar$. Let us make the substitutions below in Eqs. (21):

$$a_n \exp(i\varepsilon_+ t_1) = b_n \quad (23)$$

and eliminate a_m from the resulting equations. We then obtain the following equation:

$$\ddot{b}_n - i\varepsilon_+ \dot{b}_n + b_n |F_{mn}|^2 / \hbar^2 = 0, \quad (24)$$

with the coefficients being specified functions of the local time t_1 .

It is well known that the exchange by excitations between atoms through their resonance interaction is determined by the characteristic exchange time $\hbar/\delta E'_s$ [10]. If, at a certain point in time, a system consisting of two identical dipole atoms is in a state where one atom is excited, this excitation, as shown in [10], will be transferred to the other atom in a time $\tau' = \hbar/\delta E'_s$ through resonance interaction. With that, the time τ' required to transfer the excitation is considerably shorter than the lifetime $\Gamma_{s(a)}^{-1}$ of atoms in the symmetrical and (antisymmetrical) states,

therefore, the energy $\delta E'_s$ (12) is independent of time. In this paper, we consider a situation where the time t_1 for which a system of two interacting atoms exists is also short compared to $\Gamma_{s(a)}^{-1}$. However, in contrast to [10], we take into account, besides the interaction of the atoms with one another, their interaction with the field of real photons.

Following [1], we obtain a wave function which corresponds to a symmetric channel for the interaction of a pair of atoms with the field of real photons:

$$\begin{aligned} \tilde{\Psi}_s(t_1) = & \frac{1}{\sqrt{2}} \exp(i\varepsilon_+ t_1/2) \left[\cos(\Omega_+ t_1) - \frac{i\varepsilon_+}{2\Omega_+} \sin(\Omega_+ t_1) \right] \tilde{\varphi}_0(1)\tilde{\varphi}_0(2) - \\ & - \frac{iF_{mn}}{\hbar\Omega_+} \exp(-i\varepsilon_+ t_1/2) \sin(\Omega_+ t_1) \frac{1}{\sqrt{2}} [\tilde{\varphi}_n(1)\tilde{\varphi}_0(2) + \tilde{\varphi}_0(1)\tilde{\varphi}_n(2)] \exp(-i\delta E_s/\hbar). \end{aligned} \quad (25)$$

For an antisymmetric interaction channel we replace ε_+ with ε_- and Ω_+ with Ω_- . Here we have

$$\varepsilon_{\pm} = (\pm\delta E_s - \hbar\Delta)/\hbar, \quad \Omega_{\pm} = \sqrt{\varepsilon_{\pm}^2/4 + |F_{mn}|^2/\hbar^2}. \quad (26)$$

The wave function of the final state of an atomic pair, $\tilde{\Psi}(t_1) = [\tilde{\Psi}_a(t_1) + \tilde{\Psi}_s(t_1)]/2$, will then take the form

$$\tilde{\Psi}(t_1) = A_1\tilde{\varphi}_0(1)\tilde{\varphi}_0(2) + A_2\tilde{\varphi}_n(1)\tilde{\varphi}_0(2) + A_3\tilde{\varphi}_0(1)\tilde{\varphi}_n(2), \quad (27)$$

where the probability amplitudes for possible states of the system are given by

$$\begin{aligned} A_1 = & \frac{1}{2} \left\{ \exp(i\varepsilon_+ t_1/2) \left[\cos(\Omega_+ t_1) - \frac{i\varepsilon_+}{2\Omega_+} \sin(\Omega_+ t_1) \right] + \right. \\ & \left. + \exp(i\varepsilon_- t_1/2) \left[\cos(\Omega_- t_1) - \frac{i\varepsilon_-}{2\Omega_-} \sin(\Omega_- t_1) \right] \right\}, \end{aligned} \quad (28)$$

$$\begin{aligned} A_2 = & -\frac{iF_{nm}}{2\hbar} \left[\frac{1}{\Omega_+} \exp(-i\varepsilon_+ t_1/2) \sin(\Omega_+ t_1) \exp(-i\delta E_s t_1/\hbar) + \right. \\ & \left. + \frac{1}{\Omega_-} \exp(-i\varepsilon_- t_1/2) \sin(\Omega_- t_1) \exp(i\delta E_s t_1/\hbar) \right], \end{aligned} \quad (29)$$

$$\begin{aligned} A_3 = & \frac{iF_{nm}}{2\hbar} \left[-\frac{1}{\Omega_+} \exp(-i\varepsilon_+ t_1/2) \sin(\Omega_+ t_1) \exp(-i\delta E_s t_1/\hbar) + \right. \\ & \left. + \frac{1}{\Omega_-} \exp(-i\varepsilon_- t_1/2) \sin(\Omega_- t_1) \exp(i\delta E_s t_1/\hbar) \right]. \end{aligned} \quad (30)$$

The probability amplitudes (12) are normalized by the condition $|A_1|^2 + |A_2|^2 + |A_3|^2 = 1$. As follows from (30), at $t_1 = 0$ a system of two atoms is in a state where both atoms have an energy E_0 , i.e., $A_1 = 1$, $A_2 = A_3 = 0$. Let us consider the behavior of the function $\tilde{\Psi}(t_1)$ at subsequent points in time.

A. True resonance. Small interatomic distances

For the case of true resonance ($\Delta = 0$) for a time which is short compared to $\Gamma_{s(a)}^{-1}$, we obtain the following formulas for the probability amplitudes:

$$A_1 = \cos(\delta E_s t_1 / 2\hbar) \cos(\Omega t_1) + \delta E_s \sin(\Omega t_1) \sin(\delta E_s t_1 / 2\hbar) / 2\hbar\Omega,$$

$$A_2 = -\frac{iF_{mn}}{\hbar\Omega} \sin(\Omega t_1) \cos(3\delta E_s t_1 / 2\hbar), \quad A_3 = -\frac{F_{mn}}{\hbar\Omega} \sin(\Omega t_1) \cos(3\delta E_s t_1 / 2\hbar),$$
(31)

where $\Omega_+ = \Omega_- = \Omega = \sqrt{(\delta E_s)^2 / 4\hbar^2 + |F_{mn}|^2 / \hbar^2}$. The amplitude A_2 reaches a maximum at a time given by $t'_1 = 2\pi\hbar / 3\delta E_s$. With that, the amplitude A_3 is a minimum.

B. Nonresonance absorption of a photon. Small interatomic distances

Let us consider the case where $\Delta \neq 0$, i.e., the frequency of the real photon does not coincide with the frequency of the transition $(E_m^{(0)} - E_n^{(0)})/\hbar$. Moreover, we assume that the condition $\Delta \gg \delta E_s/\hbar$ is fulfilled. For this case, according to (26), we have $\Omega_{\pm} = \Omega = \sqrt{(\Delta^2/4) + |F_{mn}|^2/\hbar^2}$ and the amplitudes (30) become

$$A_1 = \exp(-i\Delta t_1/2) \left[\cos(\Omega t_1) + \frac{i\Delta}{2\Omega} \sin(\Omega t_1) \right],$$

$$A_2 = -\frac{iF_{mn}}{\hbar\Omega} \exp(i\Delta t_1/2) \sin(\Omega t_1), \quad A_3 = 0.$$
(32)

Thus, during nonresonance absorption of a photon two of the three possible states are realized. The state with the amplitude A_2 is realized as a result of the absorption of a photon at the position of the second atom (polarizer atom) and the transition of the first atom (observer atom) into the excited state. This state reaches a maximum at a time given by $t''_1 = \pi/2\Omega$.

C. Resonance absorption of a photon. Large interatomic distances

Given $\Delta = 0$ and $\delta E_s = 0$, the amplitudes (30) become

$$A_1 = \cos(|F_{mn}|t_1/\hbar), \quad A_2 = -\exp(i\vec{k}\vec{R}) \sin(|F_{mn}|t_1/\hbar), \quad A_3 = 0.$$
(33)

At the initial point in time $t_1 = 0$, as follows from (33), both atoms are in the ground state. However, even at an infinitely close subsequent point in time, the state $\tilde{\Phi}_n(1)\tilde{\Phi}_0(2)$ from the superposition (27) starts being realized. At the time $t'''_1 = \pi\hbar/2|F_{mn}|$ the probabilities become $|A_2|^2 = 1$ and $|A_1|^2 = 0$, i.e., one quantum bit of information is transferred from one atom to another at an infinitely large interatomic distance in the time t'''_1 . We refer to this effect as quantum teleportation in a system of two resonance atoms. This effect is quantum in nature, being

related to the superposition principle of quantum mechanics, and corresponds to the quantum means of information transfer whose characteristic time is defined as $t_1''' = \hbar/|F_{nm}|$, in contrast to the classical means of information transfer with the characteristic time t_p being the time of flight of a photon through a distance R . In accordance with the sense of the obtained solution to Eq. (24), the condition $\Gamma_{s(a)}t_1''' \rightarrow 0$ should be fulfilled. This condition is fulfilled the more precisely, the greater the amplitude of the vector potential in (22). Using the notion of the Rabi frequency [14], we obtain $t_1''' = \hbar/\sqrt{2}|d_{n0}|E_0$, where E_0 is the amplitude of the electric field of the light wave acting on the second atom.

Thus, say we have been able to create entangled states (5), (6) for two widely spaced atoms. Bouweester et al. [5] could do this using one photon source which distributes in a random manner photons randomly polarized in two different directions. Krein and Zeilinger [?] used for this purpose an electron source. In our case, one possible way of creating entangled states may be the use of two beams of double-level atoms irradiated in a random manner with a light field.

In accordance with the sense of the obtained solution (33) for a system of two resonance atoms in the field of actual photons, we represent the operation of the information system as follows: Let us assume that the system operation begins at a time $t_2 - R/c$ at the location of the second, polarizer atom when this atom is irradiated with the field of a light wave with a frequency $\omega = \omega_0$. At a local point in time, $t_1 = 0$, both atoms are in the ground state with an energy E_0 , and at a point in time t_1''' the observer atom 1 goes into an excited state with an energy $E_n = E_0 + \hbar\omega$. As this takes place, the atom 2 remains in the former state with the energy E_0 , and the average energy of the system, calculated with the help of the wave function (27) with the amplitudes (33), will be determined by the formula

$$\langle E \rangle = |A_1|^2 2E_0 + |A_2|^2 (E_0 + E_n). \quad (34)$$

The process under consideration occurs on the background of another process, having the result that the second atom goes into an excited state under the action of a resonance light wave irrespective of the presence of the first atom. To separate this process from the process of quantum teleportation, we calculate average values of the dipole moments that determine the amplitude and phase properties of these processes. The dipole transitions in the system of two atoms in view of the effect of quantum teleportation are defined by the following average:

$$\langle d_1 + d_2 \rangle_{QT} = A_1 A_2 (d_{01}) \exp(-i\omega_0 t_1). \quad (35)$$

The dipole transitions of the second atom with its correlations with the first atom not taken into account are defined by the average

$$\langle d_2 \rangle = (1/2) \sin(2\sqrt{2}E_0|d_{n0}|t_2/\hbar) \exp(-i\omega_0 t_1)(d_{0n}), \quad (36)$$

which differs from (35) only by the phase term.

For an interatomic distance $R = 30$ km, the time it takes for a photon to cover this distance with the classical means of information transfer will be $t_p = 10^{-4}$ s. The time of information transfer due to the effect of quantum teleportation is

given by $t_1''' = \hbar/\sqrt{2}|d_{0n}|E_0$. For $d_{n0} = 4.8 \times 10^{-21}$ units of the cgs electrostatic system and $E_0 = 10^{-2}$ units of the cgs electrostatic system, we obtain $t_1''' = 1.5 \times 10^{-5}$ s. Thus, the velocity of the information transfer due to the effect of quantum teleportation, $v_{QT} = R/t_1'''$, is substantially higher than the velocity of light. Nevertheless, this does not imply any contradiction with the relativity principle, since $v_{QT} = R/t_1'''$ is a phase velocity.

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