ATF-TECHNOLOGY OF COMMUNICATION BASED ON USING THE RESOURCE OF ENTANGLED STATES OF QUANTUM SYSTEMS

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Abstract

The paper introduces key elements of the new technology for data transmission and reception, entitled ATF-technology of communication. A hypothesis for the state of a quantum system that consists of two initially entangled qubits, after the completion of quantum phase transition, is formulated. An algorithm for remote modification of entanglement measure of qubits is described. A method for transmission of classical information with the use of quantum resources is developed.

Keywords

quantum computations, quantum information, qubit (quantum bit), quantum system, entangled states, quantum teleportation, entanglement measure, quantum phase transition.

Introduction

The paper introduces key elements of the new technology for data transmission and reception, entitled ***ATF****-technology of communication* (with ***A***, ***T*** and ***F*** being the first letters of the names Alexander, Tatiana and Fizuli, respectively). The basic components of the ***ATF***-technology (which are: the ***T***-hypothesis, the ***A***-algorithm and the ***F***-method) have been briefly described in [2]. Since the publication of [2], the results of the experimental research of entangled states of two-photon quantum systems (which was carried out at the Physics Department of Lomonosov Moscow State University under the guidance of Phys.-Math.Sc.D., Professor S. P. Kulik) have been received and analyzed. These results, in the broadest strokes, are presented in this paper with the agreement of Prof. Kulik. In the first approximation, we can say that the achievements of Prof. Kulik’s group, in the given experimental conditions and the instruments’ level of precision, *do not contradict* the ***T***-hypothesis (formulated in [2]), on which the ***ATF***-technology is based. We believe that it is still too early to give more encouraging statements regarding the experimental confirmation of the ***T***-hypothesis. Independent reiteration of the experiment is required. We hope that the publication of this paper will have a positive impact on further expansion and reinforcement of the experimental confirmation of the ***T***-hypothesis.

At the same time, the experimental results obtained by Prof. Kulik’s group encourage us to make a few additions to the description of the ***ATF***-technology. These additions take into account that the implementation of this technology may utilize other states of quantum systems (including those consisting of photons), different from those indicated in the paper [2]. They have been included in this paper in the form of separate notes.

As already mentioned above, the ***ATF***-technology is based on utilizing the resource of tangled (i.e. inseparable) states of quantum systems – one of the fundamentally new types of quantum physics resources that do not have counterparts in classical physics, nor have they been applied in the field of traditional computing, information and communication.

In spite of the fact that entangled quantum states do not have a counterpart in classical physics, it was established that they are not a theoretical abstraction, but rather an objective part of the surrounding reality [5]. This part exists naturally, independent from our notions. In short, this phenomenon can be described as follows.

Entangled quantum states are incident to quantum systems consisting of two or more interacting subsystems (or previously interacting and then separated). These states develop as follows: change of one subsystem affects other subsystems of the said quantum system on the instant, even if their spatial separation is extended to infinitely large distances.

At the present time, the most important achievement derived with the use of entangled quantum states resource is the quantum teleportation technology, allowing transmission of quantum states between the separated from each other parties, possessing quantum subsystems in an entangled state [12]. An integral part of this technology is the use of a classical information channel alongside with a quantum channel.

Due to the fact that it is impossible to refrain from the use of a classical information channel in quantum teleportation technology, it is impossible to implement instant communication between remote parties, even if they possess quantum system subsystems in an entangled state [13].

Aside from quantum teleportation technology there exist a number of considerable advancements in the information technology field, derived by the means of employment of the novel quantum resources, such as quantum cryptography and superdense coding [8, 12, 13]. A suggestion that further development of this field would subsequently lead to creation of instant communication between remote parties equipped with quantum system subsystems in entangled states would appear natural; however, at the present time it is considered established that such a technology is impossible to create, that is, it is impossible to implement the so-called “superluminal communication” [13].

However, in our opinion, the latter thesis needs to be specified, as it was proved (see [6, 12, 13], for example) that it is impossible to suggest instant communication between two remote parties equipped with one-qubit subsystems of a quantum system, consisting of *two* qubits in an entangled state, where by the word qubit we understand a quantum system whose states belong to a two-dimensional Hilbert space.

At the same time, there is no such proof for entangled states of quantum systems consisting of three or more qubits. There only exist statements such as “This [binding] effect seems to be in total contradiction of Einstein’s relativity theory” [6] or “the theory of relativity implies that faster than light information transfer could be used to send information backwards in time” [12], etc.

It has to be noted that the study of the entangled quantum states resource is at its cradle at the moment and it appears to be too early to dot the research in search and development of new information technology (including communications technology) that is based on this resource. It would be appropriate to quote the following thesis from a rather well-known monograph in confirmation of this statement [12]: “…the study of entanglement is in its infancy, and it is not yet entirely clear what advances in our understanding of quantum computation and quantum information can be expected as a result of the study of quantitative measures of entanglement. We have a reasonable understanding of the properties of pure states of bi-partite quantum systems, but a very poor understanding of systems containing three or more components <…> Developing a better understanding of entanglement and connecting that understanding to topics such as quantum algorithms, quantum error-correction and quantum communication is a major outstanding task of quantum computation and quantum information”. This paper is in the tideway of the above: a method of remote modification of entanglement measure (see definition in [19]) of two-qubit quantum systems is presented in Part I (as ***A***-algorithm).

The method of remote modification of entanglement measure forms the basis of our information transmission technology (in this paper presented as ***F***-method) that uses the resource of entangled states of three-qubit quantum systems. Its primary distinction from the quantum teleportation technology [12] lies in the absence of a classical information channel (that is, the classical channel component is excluded). Certain assumptions (entitled ***T***-hypothesis) are made regarding such physical phenomenon as *quantum phase transition* [10, 20]. This work presents certain arguments in favor of this hypothesis, including the results obtained from physical experiments.

The article consists of an introduction, two main parts and a conclusion. The first part describes the method of remote modification of entanglement measure of quantum systems, presented as ***A***-algorithm. The second part describes the quantum phase transition phenomenon, formulates ***T***-hypothesis in regard to its properties and states certain theoretical and experimental arguments in support of this hypothesis. The article concludes with the development and presentation of ***F***-method, allowing for transfer of information between the reciprocally distant parties equipped with subsystems of three-qubit quantum systems. The conclusion employs the results presented in the first two parts, assuming that the ***T***-hypothesis is valid.

Part I

We shall describe the method of remote modification of quantum systems entanglement measure in a style similar to the one the authors of a rather well-known monograph [12] adhere to when describing quantum teleportation technology.

Alice and Bob, while together, prepared a quantum system consisting of three qubits A, B, and C in a state

$$\left|\psi^{(3)}\right\rangle = \alpha|001\rangle + \beta|110\rangle, \tag{1}$$

where $\alpha, \beta \in \mathbf{C}$, $|\alpha| > |\beta| > 0$, $|\alpha|^2 + |\beta|^2 = 1$.

In connection with equality (1), let us draw our attention to the notation $|\kappa_1\kappa_2\cdots\kappa_r\rangle$:

$$|\kappa_1\kappa_2\cdots\kappa_r\rangle = |\kappa_1\rangle|\kappa_2\rangle\ldots|\kappa_r\rangle = |\kappa_1\rangle\otimes|\kappa_2\rangle\otimes\ldots\otimes|\kappa_r\rangle,$$

where $\kappa_1, \kappa_2, \ldots, \kappa_r \in \{0,1\}$; $|0\rangle = |\uparrow\rangle = \begin{pmatrix}1\\0\end{pmatrix}$; $|1\rangle = |\downarrow\rangle = \begin{pmatrix}0\\1\end{pmatrix}$; r is an arbitrary natural number; $\otimes$ is the outer product sign [12].

On separation, Alice keeps qubit A, while Bob takes qubits B and C. They agree that after a certain time period (coordinated in advance), Alice will also take an additional qubit D in the state $\left|\psi^{(1)}\right\rangle = \alpha|0\rangle + \beta|1\rangle$ and will expose qubits D and A to a sequence of actions (called in this work ***A***-algorithm), analogous to those Alice performs in the quantum teleportation technology [12]. As a result, as the calculations below are about to show, Bob's B and C qubit pair will represent a quantum system in an entangled state. It is assumed that there are no classical information channels between Alice and Bob who are separated from each other, hence any possibility of transmission of Alice's sequence of actions to Bob employing a classical channel is excluded.

So, what can be said of the state of the quantum system consisting of Bob's qubits and the measure of its entanglement [19], without prior exposure of the system to any influence?

The following answer is suggested to the above question: a two-qubit quantum system BC from Bob's qubits will be in of the four entangled states

$$\left|\psi_1^{(2)}\right\rangle = \frac{\alpha^2}{\sqrt{|\alpha|^4+|\beta|^4}}|01\rangle + \frac{\beta^2}{\sqrt{|\alpha|^4+|\beta|^4}}|10\rangle,\ \left|\psi_2^{(2)}\right\rangle = \frac{|01\rangle+|10\rangle}{\sqrt{2}},$$
$$\left|\psi_3^{(2)}\right\rangle = \frac{\alpha^2}{\sqrt{|\alpha|^4+|\beta|^4}}|01\rangle - \frac{\beta^2}{\sqrt{|\alpha|^4+|\beta|^4}}|10\rangle,\ \left|\psi_4^{(2)}\right\rangle = \frac{|01\rangle-|10\rangle}{\sqrt{2}} \tag{2}$$

with the probabilities

$$\frac{|\alpha|^4+|\beta|^4}{2},\ |\alpha|^2|\beta|^2,\ \frac{|\alpha|^4+|\beta|^4}{2},\ |\alpha|^2|\beta|^2, \tag{3}$$

respectively.

Justifying calculations for the given answer will be presented below, while we take a closer look at the following. Amplitude modulus $\frac{\alpha^2}{\sqrt{|\alpha|^4+|\beta|^4}}$ of the $|01\rangle$ component in the states $\left|\psi_1^{(2)}\right\rangle$ and $\left|\psi_3^{(2)}\right\rangle$ is *greater than* $|\alpha|$ and, in addition to that, the entanglement measure of each of the qubits, *A*, *B* and *C*, with the rest of the *ABC* quantum system, before completion of Alice's actions, i. e. at the time when the *ABC* quantum system was in a state $\left|\psi^{(3)}\right\rangle$ (see (1)), is equal to $2|\alpha||\beta|$, while after completion of Alice's actions following ***A***-algorithm, the entanglement measure of the *A* qubit is equal to zero (and that is natural, as the entanglement resource was expended as a result of Alice's actions); and the entanglement measure of each of Bob's qubits *B* and *C* is either equal $\frac{2|\alpha|^2|\beta|^2}{|\alpha|^4+|\beta|^4}$ (with the probability of $|\alpha|^4+|\beta|^4$), which is smaller than the initial value of $2|\alpha||\beta|$, or equal to 1 (with the probability of $2|\alpha|^2|\beta|^2$), which is greater than the initial value of $2|\alpha||\beta|$.

Thus, the following conclusion can be drawn: the entanglement resource can be both remotely increased and remotely decreased.

If the decrease of the entanglement measure of each of Bob's qubits is to a certain degree expectable and can be explained by the fact that the entanglement resource is decreasing as a result of destruction (due to Alice's actions when implementing ***A***-algorithm) of the coupling between qubit *A* and the rest of the quantum system, the increase in entanglement measure comes to much surprise (as, as a matter of fact, we obtain a technology of superluminal transmission of a physical resource to a remote point without a classical information channel), which gives hope in the possible future practical applications.

However, two following distinctive features of the concerned phenomenon have to be noted: firstly, "time allocation", that is, Alice and Bob should agree on the time for Alice's actions and Bob receives (or loses) a certain part of the corresponding physical resource after their completion; secondly, Bob's reception of the physical resource from Alice is not a determined, but rather a random phenomenon, and Bob doesn't exactly know the entanglement measure values of each of his qubits even on the assumption that Alice's actions are already completed (that is, ***A***-algorithm is completed) and he possesses that knowledge. All that he is informed of is the probability distribution of a random quantity equal to the entanglement measurements of each of his qubits. A mathematical expectation of this random quantity is equal to $4|\alpha|^2|\beta|^2$, which is lower than the initial value of $2|\alpha||\beta|$ of the entanglement measure of each of Bob's qubits. Graphs in Figure 1 bear record to this, clearly illustrating the correlation between the quantities $y=2|\alpha||\beta|=2|\alpha|\sqrt{1-|\alpha|^2}$ (solid line) and $y=4|\alpha|^2|\beta|^2=4|\alpha|^2\left(1-|\alpha|^2\right)$ (dashed line), depending on the value of $x=|\alpha|\in\left(\frac{1}{\sqrt{2}};1\right)$; in the interval $\left(\frac{1}{\sqrt{2}};1\right)$ the function $y=2x\sqrt{1-x^2}-4x^2\left(1-x^2\right)$ (dotted line), which is the difference between the aforementioned functions, reaches its maximum value at $x=|\alpha|=\frac{\sqrt{3}+1}{2\sqrt{2}}$.

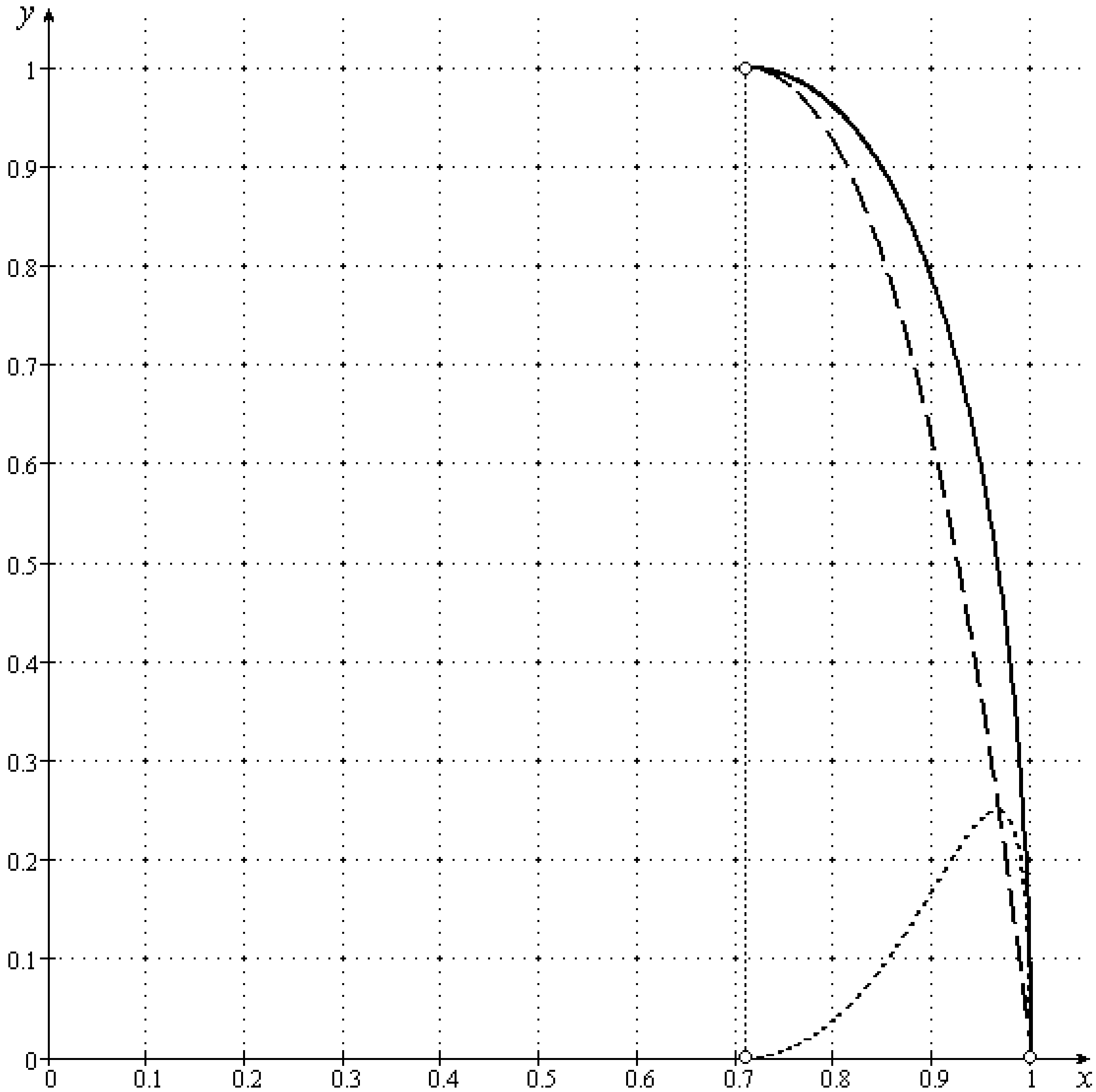

Fig. 1.

Let us now describe the sequence of Alice's actions with respect to her two qubits D and A; that is, outline ***A***-algorithm.

$\boldsymbol{A}$-algorithm

At the algorithm's input there is a state

$$\left|\psi_0^{(4)}\right\rangle = \left|\psi^{(1)}\right\rangle\left|\psi^{(3)}\right\rangle = \left(\alpha|0\rangle + \beta|1\rangle\right)\left(\alpha|001\rangle + \beta|110\rangle\right) =$$
$$= \alpha|0\rangle\left(\alpha|001\rangle + \beta|110\rangle\right) + \beta|1\rangle\left(\alpha|001\rangle + \beta|110\rangle\right)$$

of the quantum system $DABC$ consisting of four qubits D, A, B and C, of which the qubits D and A belong to Alice and the qubits B and C belong to Bob.

Step 1. Alice passes her qubits D and A through a **CNOT** element [12]. This is equivalent to applying a linear transformation with the matrix $\mathbf{CNOT} \otimes \mathbf{I}_2 \otimes \mathbf{I}_2$ to the state $\left|\psi_0^{(4)}\right\rangle$, where $\otimes$ is an outer product sign, $\mathbf{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$; $\mathbf{I}_2 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$. As a result, the state $\left|\psi_1^{(4)}\right\rangle$ of the quantum system DABC is obtained, specified by the equality:

$$\left|\psi_1^{(4)}\right\rangle = \alpha|0\rangle\left(\alpha|001\rangle + \beta|110\rangle\right) + \beta|1\rangle\left(\alpha|101\rangle + \beta|010\rangle\right).$$

Step 2. Alice passes her qubit D through the Hadamard element $\mathbf{H}$ [12], which is equivalent to applying a linear transformation with the matrix $\mathbf{H} \otimes \mathbf{I}_2 \otimes \mathbf{I}_2 \otimes \mathbf{I}_2$, where $\mathbf{H} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$, to the state $\left|\psi_1^{(4)}\right\rangle$. As a result the $DABC$ quantum system changes to the state $\left|\psi_2^{(4)}\right\rangle$, specified by the equality:

$$\left|\psi_2^{(4)}\right\rangle = \frac{\alpha}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)\left(\alpha|001\rangle + \beta|110\rangle\right) + \frac{\beta}{\sqrt{2}}\left(|0\rangle - |1\rangle\right)\left(\alpha|101\rangle + \beta|010\rangle\right),$$

which, regrouping the terms, can be re-written as follows:

$$\left|\psi_2^{(4)}\right\rangle = \frac{\sqrt{|\alpha|^4 + |\beta|^4}}{\sqrt{2}}|00\rangle\left(\frac{\alpha^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|01\rangle + \frac{\beta^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|10\rangle\right) + \alpha\beta|01\rangle\left(\frac{|01\rangle + |10\rangle}{\sqrt{2}}\right) +$$

$$+ \frac{\sqrt{|\alpha|^4 + |\beta|^4}}{\sqrt{2}}|10\rangle\left(\frac{\alpha^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|01\rangle - \frac{\beta^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|10\rangle\right) - \alpha\beta|11\rangle\left(\frac{|01\rangle - |10\rangle}{\sqrt{2}}\right).$$

Step 3. Alice conducts a measurement of her two qubits D and A in a computational basis consisting of the vectors $|00\rangle$, $|01\rangle$, $|10\rangle$ and $|11\rangle$ [12]. As a result of this measurement the four-qubit quantum system consisting of D, A, B and C can have the following subsystem states:

with a probability of $\frac{|\alpha|^4 + |\beta|^4}{2}$, the subsystem consisting of the two of Alice's qubits, D and A, is in the state $|00\rangle$, and the subsystem consisting of the two of Bob's qubits, B and C, is in the state

$$\left|\psi_1^{(2)}\right\rangle = \frac{\alpha^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|01\rangle + \frac{\beta^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|10\rangle;$$

with a probability of $|\alpha|^2|\beta|^2$, the subsystem consisting of the two of Alice's qubits, D and A, is in the state $|01\rangle$, and the subsystem consisting of the two of Bob's qubits, B and C, is in the state

$$\left|\psi_2^{(2)}\right\rangle = \frac{|01\rangle + |10\rangle}{\sqrt{2}};$$

with a probability of $\frac{|\alpha|^4 + |\beta|^4}{2}$, the subsystem consisting of the two of Alice's qubits, D and A, is in the state $|10\rangle$, and the subsystem consisting of the two of Bob's qubits, B and C, is in the state

$$\left|\psi_3^{(2)}\right\rangle = \frac{\alpha^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|01\rangle - \frac{\beta^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|10\rangle;$$

with a probability of $|\alpha|^2|\beta|^2$, the subsystem consisting of the two of Alice's qubits, D and A, is in the state $|11\rangle$, and the subsystem consisting of the two of Bob's qubits, B and C, is in the state $\left|\psi_4^{(2)}\right\rangle = \dfrac{|01\rangle - |10\rangle}{\sqrt{2}}$.

Thus, following the application of $\boldsymbol{A}$-algorithm, the quantum system BC consisting of Bob's qubits will appear in one of the states from (2) with the corresponding probability from (3).

Note 1. Instead of state $\left|\psi^{(3)}\right\rangle$, specified by (1), the following state may be utilized in $\boldsymbol{A}$-algorithm:

$$\left|\psi^{(3)}\right\rangle = \alpha|000\rangle + \beta|111\rangle, \tag{1'}$$

where $\alpha, \beta \in \mathbb{C},\ |\alpha| > |\beta| > 0,\ |\alpha|^2 + |\beta|^2 = 1$.

Then the states in (2) will be replaced by the following:

$$\begin{gathered}\left|\psi_1^{(2)}\right\rangle = \frac{\alpha^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|00\rangle + \frac{\beta^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|11\rangle,\ \left|\psi_2^{(2)}\right\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}, \\ \left|\psi_3^{(2)}\right\rangle = \frac{\alpha^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|00\rangle - \frac{\beta^2}{\sqrt{|\alpha|^4 + |\beta|^4}}|11\rangle,\ \left|\psi_4^{(2)}\right\rangle = \frac{|00\rangle - |11\rangle}{\sqrt{2}}.\end{gathered} \tag{2'}$$

Part II

We shall begin this part of the article with formulation of the following hypothesis.

***T*-hypothesis.** There exist a two-qubit quantum system and a real number $\alpha_{\text{qpt}} \ge \frac{1}{\sqrt{2}}$, such that the states of this quantum system $a|01\rangle + b|10\rangle$ and $|01\rangle$ are statistically indistinguishable during measurements in the computational basis consisting of vectors $|00\rangle$, $|01\rangle$, $|10\rangle$ and $|11\rangle$ under the condition that the inequality $|a| > \alpha_{\text{qpt}}$ is credible, where $a, b \in \mathbb{C},\ |a| > |b| > 0,\ |a|^2 + |b|^2 = 1$.

Hereinafter, the computational basis consisting of vectors $|00\rangle$, $|01\rangle$, $|10\rangle$ and $|11\rangle$ will be called simply "computational basis".

If $\boldsymbol{T}$-hypothesis is correct and BC is a corresponding quantum system consisting of two qubits B and C, we shall call the number α_{qpt} the *amplitude borderline of the quantum phase transition*; whenever it is necessary to indicate the connection of this number with the BC quantum system, we shall also use the notation $\alpha_{\text{qpt}BC}$.

The state $\left|\psi^{(2)}\right\rangle = a|01\rangle + b|10\rangle,\ a, b \in \mathbb{C},\ |a| > |b| > 0,\ |a|^2 + |b|^2 = 1$, is an entangled state of the quantum system AB; the entanglement measure $C_B\left(\left|\psi^{(2)}\right\rangle\right)$ of qubit B with the rest of the BC quantum system (i.e. with qubit C), when BC is in the state $\left|\psi^{(2)}\right\rangle$, is equal to $2|a||b|$. Provided that $\alpha_{\text{qpt}BC} \ge \frac{1}{\sqrt{2}}$, the inequality $|a| > \alpha_{\text{qpt}BC}$ is equipotent to $2|a||b| < 2\alpha_{\text{qpt}BC}\sqrt{1 - \alpha_{\text{qpt}BC}^2}$.

Then $\boldsymbol{T}$-hypothesis can be re-formulated as follows: there exist a two-qubit quantum system and a real number $\alpha_{\text{qpt}} \ge \frac{1}{\sqrt{2}}$, such that the states of this quantum system $a|01\rangle + b|10\rangle$ and $|01\rangle$

are statistically indistinguishable during measurements in the computational basis under the condition that that the BC quantum system in the state $a|01\rangle + b|10\rangle$ (where $a,b \in \mathbb{C}$, $|a| > |b| > 0$, $|a|^2 + |b|^2 = 1$) possesses a smaller entanglement measure than $C_{\text{qpt}BC} = 2\alpha_{\text{qpt}BC}\sqrt{1-\alpha^2_{\text{qpt}BC}}$.

This is the ***T***-hypothesis formulation that we will adhere to hereinafter.

Note 2. In the formulation of ***T***-hypothesis the states $a|01\rangle + b|10\rangle$ and $|01\rangle$ may be replaced by $a|00\rangle + b|11\rangle$ and $|00\rangle$, respectively. Then the ***T***-hypothesis may be re-formulated as follows: there exist a two-qubit quantum system *BC* with qubits *B* and *C* and a real number $\alpha_{\text{qpt}BC} \geq \frac{1}{\sqrt{2}}$, such that the states of this quantum system $a|00\rangle + b|11\rangle$ and $|00\rangle$ are statistically indistinguishable during measurements in the computational basis under the condition that the *BC* quantum system in the state $a|00\rangle + b|11\rangle$ (where $a,b \in \mathbb{C}$, $|a| > |b| > 0$, $|a|^2 + |b|^2 = 1$) possesses a smaller entanglement measure than $C_{\text{qpt}BC} = 2\alpha_{\text{qpt}BC}\sqrt{1-\alpha^2_{\text{qpt}BC}}$.

We shall call the number $C_{\text{qpt}BC}$ the *resource borderline of the quantum phase transition* or simply the *borderline of the quantum phase transition* of the quantum system *BC*.

Let's show that ***T***-hypothesis does not contradict the modern understanding of a well-known phenomenon, the "quantum phase transition" [10]. With this purpose in mind we shall note that the electron, proton, neutron, nuclear and other spins with a spin number of ½ are natural two-level quantum cells – that is, qubits [4, 7]. Projection of each spin on a selected direction (for example, as it is often assumed, along the *Z*-axis) can be pointing either upwards (along the direction, denoted $|\uparrow\rangle = |0\rangle = \begin{pmatrix}1\\0\end{pmatrix}$) or downwards (opposing the direction, denoted $|\downarrow\rangle = |1\rangle = \begin{pmatrix}0\\1\end{pmatrix}$).

Consider a quantum system consisting of two such qubits, in a constant external magnetic field with the magnetic induction vector $\mathbf{M}$ pointing along the *Z*-axis, i. e. $\mathbf{M} = (0, 0, M)$, where M is the magnetic induction vector modulus, $M \geq 0$. We shall assume that qubits in the *BC* quantum system are connected together through an *isotropic Heisenberg antiferromagnetic interaction* (the so-called two-spin XXX Ising model) [10] with the spin interaction constant $J > 0$ [14]. In this case the *BC* quantum system has the following stationary states [1]:

$$\left|\psi_1^{(2)}\right\rangle = |11\rangle e^{-\left(\frac{i}{\hbar}\right)E_1 t}, \quad \left|\psi_2^{(2)}\right\rangle = |00\rangle e^{-\left(\frac{i}{\hbar}\right)E_2 t},$$
$$\left|\psi_3^{(2)}\right\rangle = \left(\sqrt{\varepsilon}|01\rangle + \sqrt{1-\varepsilon}|10\rangle\right) e^{-\left(\frac{i}{\hbar}\right)E_3 t}, \quad \left|\psi_4^{(2)}\right\rangle = \left(\sqrt{1-\varepsilon}|01\rangle - \sqrt{\varepsilon}|10\rangle\right) e^{-\left(\frac{i}{\hbar}\right)E_4 t}, \tag{4}$$

where

$$\varepsilon = \frac{1}{2}\left(1 - \frac{X}{\sqrt{1+X^2}}\right); \tag{5}$$

$$X = \frac{\omega_1 - \omega_2}{J} = \frac{M}{J}(\nu_1 - \nu_2); \tag{6}$$

ω_1, ω_2 are the resonance frequencies of the *B* and *C* spins; $\omega_1 = \nu_1 M$, $\omega_2 = \nu_2 M$; ν_1, ν_2 are the gyromagnetic relations of the *B* and *C* spins; E_k is the energy of $\left|\psi_k^{(2)}\right\rangle$ stationary state, $k \in \{1,2,3,4\}$,

$$E_1 = \left(\frac{J}{4} + \frac{\omega_1 + \omega_2}{2}\right)\hbar; \; E_2 = \left(\frac{J}{4} - \frac{\omega_1 + \omega_2}{2}\right)\hbar;$$

$$E_3 = \left(-\frac{J}{4} + \frac{J\sqrt{1+X^2}}{2} \right)\hbar; \; E_4 = \left(-\frac{J}{4} - \frac{J\sqrt{1+X^2}}{2} \right)\hbar; \tag{7}$$

t is time, $\hbar$ is the reduced Planck constant, $i = \sqrt{-1}$ is the imaginary unit.

Among the stationary states (4) of the BC quantum system let's look closely at the states $\left|\psi_3^{(2)}\right\rangle$ and $\left|\psi_4^{(2)}\right\rangle$.

If $\nu_1 = \nu_2$, then $\omega_1 = \omega_2$ and hence $X = 0$ and $\varepsilon = ½$ (see (6), (5)), thus inclining credibility of the equalities:

$$\left|\psi_3^{(2)}\right\rangle = \left(\frac{|01\rangle + |10\rangle}{\sqrt{2}} \right) e^{-i\left(\frac{J}{4}\right)t}, \; \left|\psi_4^{(2)}\right\rangle = \left(\frac{|01\rangle - |10\rangle}{\sqrt{2}} \right) e^{-i\left(\frac{-3J}{4}\right)t}. \tag{8}$$

Resulting from the equalities (8), when $\nu_1 = \nu_2$, amplitudes of the stationary states $\left|\psi_3^{(2)}\right\rangle$, $\left|\psi_4^{(2)}\right\rangle$ and their energies do not depend on the magnitude of modulus M of the magnetic induction vector. Also in these states the entanglement measure of the BC quantum system does not depend on the magnetic field, being in this case equal to the maximum value of 1.

Now consider the case when $\nu_1 \neq \nu_2$. Without confining the generalities, let's assume for clarity that $\nu_1 < \nu_2$. Then $\omega_1 < \omega_2$ and, hence, $X < 0$ when $M > 0$ and X decreases as M increases (see (6)). It follows from this and from (5) that the quantity $\sqrt{\varepsilon}$, equal to the left amplitude modulus of the state $\left|\psi_3^{(2)}\right\rangle$ and the right amplitude modulus of the state $\left|\psi_4^{(2)}\right\rangle$ (see (4)), increases with the increase of M, and its minimal value, which is equal to $\frac{1}{\sqrt{2}}$, is achieved at $M = 0$, that is, in the absence of an external magnetic field. The limit value of $\sqrt{\varepsilon}$ at $M \to \infty$ is equal to 1 and, as it can be judged from (5), it is not achievable at any finite value of M. At the same time the quantity $\sqrt{1-\varepsilon}$, equal to the right amplitude modulus of the state $\left|\psi_3^{(2)}\right\rangle$ and the left amplitude modulus of the state $\left|\psi_4^{(2)}\right\rangle$ (see (4)), decreases with the increase of M, and its maximal value, which is equal to $\frac{1}{\sqrt{2}}$, is achieved at $M = 0$, that is, in the absence of an external magnetic field. The limit value of $\sqrt{1-\varepsilon}$ at $M \to \infty$ is equal to 0 and, as it can be judged from (5), it is not achievable at any finite value of M. In addition, the entanglement measure of qubits of the BC quantum system in the states $\left|\psi_3^{(2)}\right\rangle$ and $\left|\psi_4^{(2)}\right\rangle$, which is

$$C_B\left(\left|\psi_3^{(2)}\right\rangle\right) = C_B\left(\left|\psi_4^{(2)}\right\rangle\right) = 2\sqrt{\varepsilon}\sqrt{1-\varepsilon} = \frac{1}{\sqrt{1+X^2}} = \frac{J}{\sqrt{J^2 + M^2(\nu_1 - \nu_2)^2}}, \tag{9}$$

decreases with the increase of M and takes on its maximal value of 1 when $M = 0$, that is, in the absence of the external magnetic field.

Consequently, judging by (9), the entanglement measure of qubits of the BC quantum system in the states $\left|\psi_3^{(2)}\right\rangle$ and $\left|\psi_4^{(2)}\right\rangle$ converges to 0 when $M \to \infty$, but does not reach its limit value of 0 at any finite value of M.

However, on the other hand, it follows from the results in [3, 10, 11, 16] that starting from a certain value of $M_{\mathrm{qpt}BC}$ of the permanent external magnetic field magnetic induction vector modulus, the entanglement measure of qubits of quantum system BC abruptly takes on a zero value. This is exactly the phenomenon of *quantum phase transition* [10]. Hence, it would be natural to assume in accordance with (9) and definition of the $C_{\mathrm{qpt}BC}$ parameter that

$$C_{\mathrm{qpt}BC} \geq \frac{J}{\sqrt{J^2 + M_{\mathrm{qpt}BC}^2 (\nu_1 - \nu_2)^2}}. \tag{10}$$

Thus, on fulfillment of $M \geq M_{\mathrm{qpt}BC}$, the stationary states of a quantum system are separable. In some of the aforementioned works (for example, in [3, 16]) this phenomenon is explained from the positions of classical physics (and it is then declared that such an explanation does not contradict the quantum mechanics provisions), based on the "obvious notions of magnetic moments precession", and it is noted that it is analogous to the phenomenon discovered by Paschen and Back in 1912 (and thus entitled Paschen-Back Effect), implying disruption of a spin-orbit coupling of an atom in a strong magnetic field [11]. The difference is only that the case of two spins in a magnetic field is a question of disruption of a spin-spin coupling in a strong magnetic field due to the fact that in a sufficiently large magnetic field the total interaction energy of magnetic angular momenta (corresponding to the concerned spins) with the magnetic field becomes greater than the spin-spin coupling energy.

The described effect is examined in good detail in a rather well-known work [15] using Hydrogen atom as an example. Both the stationary state energies and the stationary states themselves (in the form of 4-dimensional Hilbert space vectors) are derived. If we assume that qubit B is the electron spin, and qubit C is the proton spin in a Hydrogen atom, then the results derived in [15] (accurate within certain designations and specifications) concur with (7) and (4). Furthermore, in [15] it is clearly pointed which states the states $\left|\psi_3^{(2)}\right\rangle$ and $\left|\psi_4^{(2)}\right\rangle$ change to, when condition $M \geq M_{\mathrm{qpt}BC}$ is fulfilled (the so-called "strong magnetic field" [3, 11, 15, 16]), which in this case brings about the fact that the entanglement measure of qubit B with the rest of quantum system BC (i. e. with qubit C) does not exceed the value of $C_{\mathrm{qpt}BC}$. The new states appear to be $|01\rangle$ and $|10\rangle$, respectively, each of which does not statistically differ from oneself when measured in the computational basis.

Thus, ***T***-hypothesis does not contradict the established notions of physics concerned with the quantum phase transition phenomenon. However, the following has to be noted. The works [3, 10, 11, 15, 16], which we referenced earlier, are only concerned with stationary states, whereas the ***T***-hypothesis does not have this limitation. The hypothesis is concerned with arbitrary states in general, not necessarily the stationary ones. Thus there is a need for experimental verification of the ***T***-hypothesis. Such verification was lead off at the Physics Department of Lomonosov Moscow State University under the guidance of Professor S. P. Kulik. A brief description of the experiment carried out and the results obtained by Prof. Kulik is represented by the following note.

Note 3. The source of entangled states is the polarization state of a pair of photons that are emitted during the process of spontaneous optical parametric down-conversion [9]. The pump is a diode laser with feedback at the wavelength of 408 nm and bandwidth of less than 0.1 nm. Bi-photon radiation is in the degenerate noncollinear mode at the wavelength of 816 nm and bandwidth of 10 nm. Pairs of photons are generated by two 1-mm-thick crystals of beta-ammonium borate with type-I phase matching oriented at 90° with respect to each other [18]. The state of bi-partite system emerging at the output of the crystals has the following form:

$$|\psi_{12}\rangle = \alpha|H_1\rangle|H_2\rangle + \beta|V_1\rangle|V_2\rangle,\ |\alpha|^2 + |\beta|^2 = 1,$$

where the indices refer to the photons, and H and V denote their polarization – horizontal and vertical, respectively.

The ratio between the real amplitudes α and β is varied by rotating the half-wave plate installed in the pump laser beam by an angle of φ:

$$|\alpha| = \cos(2\varphi),$$

so that at $\varphi = 0^0$ only pairs from the first crystal in the state of $|H_1\rangle|H_2\rangle$ are emitted; while at $\varphi = 45^0$ – only from the second crystal, in the state of $|V_1\rangle|V_2\rangle$.

For each plate orientation, i.e. for α and β amplitude ratio, the procedure of full polarization tomography of bi-photon state is executed and the full density matrix is restored [17]. The measurements were carried out in such a way that the number of registered events (coinciding photocounts, which indicate registered pairs) would be 5×10^4. The procedure was repeated 5 times for a given α, and then by rotating the plate in the pump a new value was set. This resulted in the total number of 2.5×10^5 for each given α. It was established that at $|\alpha|^2 \geq 0{,}9951$ the states $|\psi_{12}\rangle = \alpha|H_1\rangle|H_2\rangle + \beta|V_1\rangle|V_2\rangle$ and $|H_1\rangle|H_2\rangle$ are statistically indistinguishable.

Thus, the obtained results do not contradict ***T***-hypothesis formulated in Note 2.

Further in this work we will assume that ***T***-hypothesis is true and that the discussed quantum system BC satisfies the conditions of this hypothesis. Considering this, and the additional assumption that the value of amplitude α in (1) satisfies the inequality

$$\frac{|\alpha|^2}{\sqrt{|\alpha|^4 + |\beta|^4}} > \alpha_{\mathrm{qpt}BC}, \tag{11}$$

allows for a replacement of states (2) with probabilities (3) in Part I of the article (while measuring in the computational basis) by states

$$|01\rangle, \ \frac{|01\rangle + |10\rangle}{\sqrt{2}}, \ \frac{|01\rangle - |10\rangle}{\sqrt{2}} \tag{12}$$

with probabilities

$$|\alpha|^4 + |\beta|^4, \ |\alpha|^2|\beta|^2, \ |\alpha|^2|\beta|^2, \tag{13}$$

respectively.

Thus, if we return to the first part of the present article, we have the following.

If Alice did not do anything to her qubits A and D, Bob's qubits BC after his conducted measurements in the computational basis will appear in state $|01\rangle$ with the probability of

$$P(|01\rangle) = |\alpha|^2. \tag{14}$$

If Alice (prior to Bob's actions) applied ***A***-algorithm to her qubits A and D, Bob's qubits B and C after his conducted measurements in the computational basis will appear in state $|01\rangle$ with the probability of

$$P(|01\rangle) = |\alpha|^4 + |\beta|^4 + |\alpha|^2|\beta|^2 = |\alpha|^2\left(|\alpha|^2 + |\beta|^2\right) + |\beta|^4 = |\alpha|^2 + |\beta|^4. \tag{15}$$

Note 4. On the basis of Notes 1 and 2, the equalities (14) and (15) may be replaced by the following equalities:

$$P(|00\rangle) = |\alpha|^2, \tag{14'}$$

$$P(|00\rangle) = |\alpha|^4 + |\beta|^4 + |\alpha|^2|\beta|^2 = |\alpha|^2\left(|\alpha|^2 + |\beta|^2\right) + |\beta|^4 = |\alpha|^2 + |\beta|^4. \tag{15'}$$

If the value of $\alpha_{\mathrm{qpt}BC} = \tau > \dfrac{1}{\sqrt{2}}$ is known, inequality (11) induces credibility of the following limitation on the modulus amplitude values $|\alpha|$ of state (1) of a three-qubit system ABC:

$$|\alpha| \in \left(\sqrt{\frac{\tau^2 - \tau\sqrt{1-\tau^2}}{2\tau^2 - 1}}; \sqrt{\frac{\tau^2 + \tau\sqrt{1-\tau^2}}{2\tau^2 - 1}}\right). \tag{16}$$

Since at $1 > \tau > \dfrac{1}{\sqrt{2}}$ the inequality

$$\sqrt{\frac{\tau^2-\tau\sqrt{1-\tau^2}}{2\tau^2-1}} > \frac{1}{\sqrt{2}} \tag{17}$$

and the double inequality

$$\sqrt{\frac{\tau^2-\tau\sqrt{1-\tau^2}}{2\tau^2-1}} < \tau \le \sqrt{\frac{\tau^2+\tau\sqrt{1-\tau^2}}{2\tau^2-1}} \tag{18}$$

are credible, it follows from (16) that the preferred values for $|\alpha|$ appear to be those satisfying the condition

$$|\alpha| \in \left(\sqrt{\frac{\tau^2-\tau\sqrt{1-\tau^2}}{2\tau^2-1}} ; \tau \right), \tag{19}$$

and, due to physical concerns [1], the ones located as close as possible to the left edge $\sqrt{\frac{\tau^2-\tau\sqrt{1-\tau^2}}{2\tau^2-1}}$ of the interval (19).

Conclusion

In conclusion of this article we shall present the ***F***-method, designed for transmission of a one-bit message from one party to another under the condition that the two are spatially separated from each other and do not have a classical information channel. ***F***-method utilizes only quantum resources.

It has to be noted that in order to transmit a *k*-bit message (where $k \in \mathbb{N}$), ***F***-method is employed *k* times, transmitting one bit at a time. Therefore there are possibilities for ultimate multi-sequencing.

We shall outline the description of ***F***-method of message transmission consisting of one bit in a manner similar to the one the authors of a well-known monograph [12] adhere to when describing quantum teleportation technology.

Alice and Bob met long ago, but now live far apart. While together, they generated an L of sets of three qubits $A_iB_iC_i$ in the states:

$$\left|\psi_i^{(3)}\right\rangle = \alpha|001\rangle + \beta|110\rangle,\ i \in \{1,2,\dots,L\};\ \alpha,\beta \in \mathbb{C},\ |\alpha| > |\beta| > 0,\ |\alpha|^2 + |\beta|^2 = 1,$$

where the α parameter is selected in such a way that condition (11) is fulfilled.

Note 5. On the basis of Notes 1 and 2, the states

$$\left|\psi_i^{(3)}\right\rangle = \alpha|001\rangle + \beta|110\rangle,\ i \in \{1,2,\dots,L\};\ \alpha,\beta \in \mathbb{C},\ |\alpha| > |\beta| > 0,\ |\alpha|^2 + |\beta|^2 = 1$$

may be replaced by the following states:

$$\left|\psi_i^{(3)}\right\rangle = \alpha|000\rangle + \beta|111\rangle,\ i \in \{1,2,\dots,L\};\ \alpha,\beta \in \mathbb{C},\ |\alpha| > |\beta| > 0,\ |\alpha|^2 + |\beta|^2 = 1.$$

On separation Alice took the first qubit A_i from each of the sets of three qubits, while Bob took the remaining second and third qubits B_i and C_i from each of the sets. In addition to that, Alice also generated for herself another L of D_i qubits in the states:

$$|\psi_i\rangle = \left|\psi_i^{(1)}\right\rangle = \alpha|0\rangle + \beta|1\rangle,\ i \in \{1,2,\dots,L\},$$

correspondingly.

They agreed that after 3 years on a certain hour (for example, at 19:00) of a certain day (for example, the 1st of January) Alice should transfer Bob one bit of classical information. It is assumed, as stated above, that *there exists no classical information channel* between Alice and Bob. The bit of classical information is hence transferred exclusively employing the quantum resources available to them.

Is the formulated task solvable, that is, would it be possible for Bob to receive a one-bit message, transmitted by Alice? If it is, what would be the values of parameters L and α sufficient for that to happen?

Schematically the solution looks as follows: Alice performs the following actions before the time mentioned above. If the value of the transmitted one-bit message is equal to zero, she does nothing. If the value of the transmitted one-bit message is equal to one, she performs a sequence of actions with all of her $2L$ qubits (that sequence, specified for transmission of a bit with the value of 1, will be described below) and finishes this work before 19:00 of the agreed day. While Bob conducts the measurement of his L B_iC_i qubit pairs in the computational basis after 19:00. If Alice did nothing, then obviously as a result of Bob's measurement the qubit pair B_iC_i will appear in state $|01\rangle$ with the probability of $P(|01\rangle)=|\alpha|^2$. If Alice completed all the actions meant for transmission of a bit with the value of 1, then we assume that as a result of Bob's measurement the qubit pair B_iC_i will appear in state $|01\rangle$ with the probability of $P(|01\rangle)=|\alpha|^2+|\beta|^4$ (the corresponding justification will be given below, after description of Alice's actions on transmission of a bit with the value of 1). Then Bob processes the measurement results of his L pairs of qubits, which involves testing the simple statistical null hypothesis

$$H_0 : P(|01\rangle)=|\alpha|^2$$

against the alternative, which is also a simple hypothesis,

$$H_1 : P(|01\rangle)=|\alpha|^2+|\beta|^4,$$

on the basis of the L-sized sample.

If hypothesis H_0 is true, then Bob assumes that the bit that Alice transmitted has a value of 0. Otherwise, i. e. when H_0 is rejected, the bit is assumed to be equal to 1. It is then clear that a sufficient value of L will be defined by the specified level of significance, false negative and value of amplitude α.

Let us now describe Alice's actions when transmitting a bit with the value of 1 to Bob. Alice performs L iterations and the same sequence of actions in each iteration. Alice's actions in i-th iteration ($i \in \{1,2,\dots,L\}$) are as follows.

Alice uses ***A***-algorithm, described in Part I of the present work, with her pair of qubits D_iA_i. As a result of this, Bob's pair of qubits B_iC_i will appear in one of the four entangled states (2) with the corresponding probabilities (3).

Now we shall note that each of Bob's qubit pairs B_iC_i forms a quantum system, similar to quantum systems for which ***T***-hypothesis is true (as parameter α is selected in a way to satisfy condition (11)), formulated in Part II of the present work. Then Bob's qubit pair B_iC_i will appear in one of the three states (12) with the corresponding probabilities (13). Therefore, after Bob conducts the measurements in the computational basis, the B_iC_i qubit pair will appear (in accordance with (15)) in the state $|01\rangle$ with the probability of $P(|01\rangle)=|\alpha|^2+|\beta|^4$.

Finally, speaking of sufficient values for parameter α for implementation of ***F***-method, the values of α that satisfy condition (19) can be pointed out.

Note 6. On the basis of Notes 1, 2 and 5, the H_0 и H_1 hypotheses may be written as follows:

$$H_0 : P(|00\rangle)=|\alpha|^2,$$

$$H_1 : P(|00\rangle)=|\alpha|^2+|\beta|^4.$$

Note 7. Actually, in the ***F***-method Bob does not need to measure both qubits in every pair. It will be enough to measure one qubit of each pair (either the first one or the second one), since the result of such measurement is uniquely associated to the result of the entire pair.

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Summary

ATF-technology of communication based on using the resource of entangled states of quantum systems

The paper introduces key elements of the new technology for data transmission and reception, entitled ***ATF***-technology of communication (with A, T and F being the first letters of the names Alexander, Tatiana and Fizuli, respectively). It is based on using the resource of entangled states of quantum systems – one of the conceptually new resources of quantum physics. The basic components of the ***ATF***-technology of communication are: the ***T***-hypothesis, the ***A***-algorithm and the ***F***-method.

The ***T***-hypothesis is a mathematically formulated assumption about the state of a quantum system that consists of two initially entangled qubits, after the completion of quantum phase

transition. The formulation of this hypothesis was inspired by the results of the analysis of available theoretical and experimental data on the physical phenomenon of quantum phase transition.

The paper gives a brief description of the experimental research of entangled states of two-photon quantum systems, which was carried out at the Physics Department of Lomonosov Moscow State University in 2014. The results obtained can be considered the first steps towards experimental confirmation of the ***T***-hypothesis.

The second component of the ***ATF***-technology of communication, which is also described in the paper, is the ***A***-algorithm for remote modification of entanglement measure of qubits. The special features of this algorithm, which make it fundamentally different from the well-known technology called “quantum teleportation”, are: usage of three-qubit quantum systems to form a quantum communication channel and total exclusion of the classical communication channel between the transmitting and receiving parties.

Under the condition of prior assumption that the ***T***-hypothesis is true, the ***F***-method – the third component of the ***ATF***-technology of communication – provides a basis for bit-by-bit transmission of a binary message in a one-way communication session that consists of two consecutive stages. The quantum communication channel is formed by three-qubit quantum systems in entangled state, whose subsystems are distributed among the parties as follows. One-qubit subsystems belong to the sender. Two-qubit subsystems belong to the recipient.

The one-way communication session for transmitting one bit consists of the following stages.

In stage 1 the sender applies the ***A***-algorithm to his array of qubits if the value of the transmitted bit is 1. If the value of the transmitted bit is 0, no action is required.

In stage 2 the recipient measures his qubits and processes measurement results. The processing involves solving the statistical problem of testing a simple null hypothesis against the alternative (which is also a simple hypothesis) with the sample of a given size. If the simple hypothesis is correct, then the recipient assumes that the transmitted bit has a value of 0. Otherwise, the bit value is assumed to be 1.