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Review

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The Second Quantum Revolution: Development of Subatomic Quantum Nanotechnologies of Intelligent Materials

The article analyzes the future development of quantum nanotechnology based on attosecond physics of the subatomic level of the condensed state. The ways of realizing the main achievements of the second quantum revolution in subatomic nanotechnologies of materials, namely quantum entanglement, quantum contextuality and quantum dissipativity are considered. The theoretical analysis of the prospects for this direction in the development of quantum subatomic nanotechnologies has been carried out within the framework of the well-known theory of thermal field dynamics of the condensed state. The analysis shows that subatomic entanglement of electron pairs is realized by attosecond single-cycle photons. The entangled electron pairs form the interfaces of supra-atomic capsules — quantum nanoelectromechanical systems (NEMS) of the condensed state of the material. The Coulomb blockade of quantum NEMS interfaces is complemented by the fact that they are controlled by the infrastructure of subatomic two-electron sensors and actuators located at the interface boundaries. When the primary subatomic interfaces of NEMS function, secondary supra-atomic scale entangled pairs of electrons are generated, which dissipate the NEMS energy and form a dissipative multilevel hierarchy of condensed state interfaces at higher spatio-temporal scales of intelligent materials.

Keywords: the second quantum revolution, subatomic attosecond physics, thermo-field dynamics, quantum entanglement, quantum contextuality, quantum dissipativity, quantum nanotechnology, intelligent materials.

Contents

Introduction

In the coming years, production based on quantum technology of the so-called second quantum revolution will expand rapidly, covering high-tech industries [1]. One of the main areas of research is subatomic quantum technologies. Their specificity is determined by quantum effects on the space-time scales of the subatomic level of matter, limited from below by the size of the inner electron shells closest to the nucleus, and from above — by the length of the outer electron shells of the atom. It is assumed that individual attosecond electromagnetic pulses are key tools for manipulating quantum effects in the subatomic region of matter. The solution to these questions is the main problem of attophysics, which has been rapidly developing in the last decade [2–5]. There is no doubt that attosecond subatomic technologies will play a key role in the second quantum revolution and become one of the breakthrough directions of its development.

At the supra-atomic level, there are many combinations of the dynamics of various one-electron excitations with vibrational-rotational-translational modes of excitation of the nuclear subsystem and the pathways of chemical reactions. All these femtosecond processes in different atomic-molecular systems have been well studied over the last quarter of a century in the framework of femtochemistry [6].

At present, the attosecond quantum dynamics of an electron at the subatomic level is intensively studied in attophysics [7–10]. Attosecond pulses are an ideal tool for studying the effects of electron correlation with time resolution in the subatomic region Electronic strong correlation, which is determined by the interaction of electrons in a many-electron system at subatomic areas, plays a fundamental role in several physical processes and characterizes several nonequilibrium processes, for example, the relaxation of excited states of atoms and molecules irradiated with XUV pulses. The dynamics of these states can lead to various phenomena at the supra-atomic level, such as Auger decay in atoms, interatomic Coulomb decay, or charge migration in atomic-molecular systems.

Although a complete characterization of the time-dependent correlated motion of two electrons can only be obtained using the attosecond pumping method and the attosecond probe, so far only alternative methods based on a combination of attosecond XUV and femtosecond IR pulses have been used. In this regard, the effects of the appearance of entangled pairs of electrons generated by an attosecond pulse in the subatomic region cannot be experimentally studied yet. The problems of the second quantum revolution indicate the prospects of studying the attosecond pulsed entanglement of subatomic electron pairs, which can appear at the next supra-atomic scale level — the basic one for quantum nanotechnology [11–14]. The purpose of this article is to provide a theoretical analysis of the possibilities for the development of the second quantum revolution in this direction.

The layout of the article is as follows. This article discusses three aspects of the second quantum revolution in the development of a fundamentally new quantum subatomic nanotechnology using the effects of quantum entanglement, contextuality and dissipativity. Section 1 analyzes the mechanism of implementation of pulsed attosecond quantum entanglement of subatomic electron pairs. In Section 2, we will consider the mechanism of the quantum contextuality of measuring and controlling electron-nuclear systems at the supra-atomic level using subatomic entangled electron pairs. The final Section 3 discusses the role of the quantum dissipativity of secondary supra-atomic entangled electron pairs in the formation of the infrastructure of quantum smart materials.

1. Attosecond quantum entanglement of subatomic electrons

To fully understand the influence of the interrelated motion of electrons on the course of nonequilibrium processes in matter, it is necessary to study in detail the effects of the rearrangement of the correlated motion of electron pairs at the subatomic scale level caused by a separate attosecond pulse. It is known that the quantum mechanics of an electron in the matter is determined by its two Coulomb electrostatic interactions with nuclei and other electrons. There is one-electron interaction with protons of nuclei (e^{-}–p), as well as two-electron interactions (e^{-}–e^{-}). Under the adiabatic approximation of quantum mechanics, electron-nuclear particles of matter endow it in stationary states with an atomic-molecular structure. This structure is specified by the topology of the electron density distribution $n(r)$ in the physical space R^3. Due to the identity of N-electrons in a quantum system, the distribution $n(r)$ is only a function of the probability density $n_1(r)$ of finding a single electron at the point r: $n(r) = N \cdot n_1(r)$. The one-electron interaction (e^{-}–p) establishes the supra-atomic scale level of atomic-molecular systems in materials. It was shown [11] that restrictions from below on the fundamental supra-atomic scale length is specified by the (e^{-}–p) atomic Bohr radius $a_0 = \frac{\hbar^2}{m_0 e^2}$.

In quantum field electrodynamics of a condensed state at the subatomic level, in addition to two above-mentioned electrostatic interactions of an electron, its gauge kinematic relationship (e^{-}~χ) with the electromagnetic γ-field begins to play an important role [15]. This relationship imposes restrictions from below on the subatomic scale of the quantum dynamics by the Compton length of the electron $\bar{\lambda}_e = \frac{\hbar}{m_0 c}$.

The fundamental scales of the subatomic and supra-atomic dynamics of an individual electron in a condensed state are related by the fine structure constant of the physical vacuum $\alpha = \frac{e^2}{\hbar c}$ as follows [11]:

$$a_0 = \bar{\lambda}_e / \alpha . \qquad (1)$$

It is known that the interaction of two electrons in physical space is not reduced only to instantaneous electrostatic interaction (e^{-}–e^{-}) due to the finite velocity of propagation of perturbations of the gauge electromagnetic field. Within the framework of the concept of the thermofield dynamics, it has been shown that in the subatomic region of the nonequilibrium condensed state, the attosecond χ-mode of the kinematic density wave of the gauge electromagnetic field is capable of entangling a pair of electrons like a string (e^{-}~χ~e^{-}) [12]. The mechanism of quantum entanglement is that a strongly correlated motion is established inside an entangled pair of electrons as a result of spontaneous condensation χ-Goldstone mode of a static kinematic density wave, according to the formula: $\chi_0(x) \rightarrow \chi_0(x) + \chi$ [11, 15]. As a result, for an entangled pair of electrons, the distance between them does not change, and their lifetime in the pair is synchronized.

The quantum state $\Psi(r_1,t_1;r_2,t_2)$ of an entangled electron pair with the space-time coordinates of the first (r_1, t_1) and second (r_2, t_2) electrons synchronized in the pair lifetime $t = (t_1 + t_2) / 2$ and at a fixed electron displacement in the pair $R = (r_1 - r_2)$ is described by a kinematic density wave $\phi_R(r\,|\,t)$ of their center of mass with spatial coordinate $r = (r_1 + r_2) / 2$:

$$\Psi(r_1,t_1;r_2,t_2) = \phi_R(r\,|\,t). \tag{2}$$

The kinematic density wave $\phi_R(r\,|\,t)$ of the bielectron is enclosed in a compact spatial loggia in the material [11]. The characteristic length of the loggia L is determined by the limiting distance of propagation of the quantum kinematic density wave $\phi_R(r\,|\,t)$ during the existence of a subatomic entangled pair of electrons. If we denote by $|R|$ the fixed distance between the entangled electrons of the pair ($a_0 \geq |R| \geq \lambdabar_e$), then the length L will be determined by the ratio: $L = |R|/\alpha$, where α is the fine structure constant. The L parameter sets the next supra-atomic scale level of the material: $a_0 / \alpha \geq L \geq a_0$.

The restructuring effects of the correlated motion of electron pairs at the subatomic level caused by a single attosecond pulse are presented in Figure 1. The diagram shows the main stages of the generation of an entangled electron pair in the subatomic region of one of the atoms and further propagation of its kinematic density wave to neighboring atoms inside a compact spatial loggia at the supra-atomic scale level of the material.

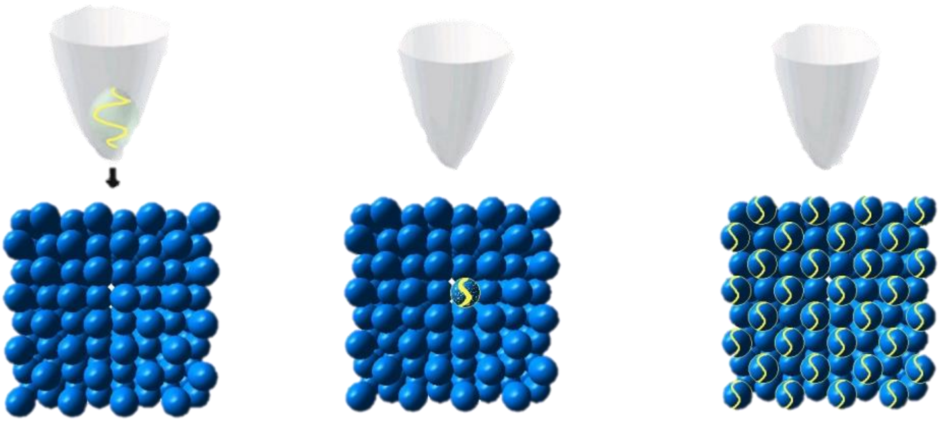

Figure 1. Attosecond impulse mechanism of subatomic formation of an entangled pair of electrons (e^{-}~χ~e^{-}) and propagation of a kinematic wave of bielectron density inside a spatial loggia at the supra-atomic scale level of materials

As can be seen from Figure 1, during the attosecond propagation time δτ of the kinematic density wave of a subatomic entangled pair of electrons, a topologically closed interface of separated electron charges appears at the boundary of the supra-atomic loggia. The interface creates a Coulomb electrostatic blockade of the nuclear-electronic subsystem inside the topological capsule, forming a composite quantum nanoelectromechanical system (NEMS). Thus, the quantum-dimensional NEMS is a hybrid comprising a capsule of the boundary kinematic density wave of a subatomic entangled electron pair with a thickness $|R|$ less than 0.1 nm, inside which the electron-nuclear subsystem is enclosed. The NEMS capsule has a supra-atomic length of 0.1 to 10 nanometers, containing from one to a thousand atoms.

2. Quantum contextuality of measurement and control of hybrid NEMS

Let us turn now on the example of hybrid NEMSs to consideration of application in the most promising quantum technologies of another cornerstone idea of the second quantum revolution — the effect of contextuality perception and control of quantum objects in materials. This question is a special case of a more general problem of the quantum contextuality. Currently, this most “quantum” of all quantum phenomena has developed a sharp controversy [16]. Quantum contextuality is a feature of the phenomenology of quantum mechanics, according to which measurements of observables of a quantum object cannot be regarded simply as revealing pre-existing values. Firstly, because at the moment of measurement, a multi-wave reduction of the quantum state of the object occurs and, secondly, the result of measuring the quantum observable depends on switching properties of measuring devices taking part in the measurement. In connection with the above remarks, below we will consider the quantum mechanism of the contextuality process of the stepwise unfolding in time of the NEMS motion in the material.

In fact, in the case of a hybrid quantum NEMS, the capsule interface acts as a measuring device in the attosecond pulsed mode and a control device in the femtosecond pulsed mode for the internal electron-nuclear component of the NEMS. Let us show it.

It has been shown earlier [11–14] that after the completion of the propagation of the kinematic density wave, the electronic state Φ_1 of a subatomic entangled pair has the following expression:

$$\Phi_1 = 2^{-1/2}(\Phi_{-1} + \Phi_{+1}). \quad (3)$$

Diagram in the Figure 2 shows the charge separation scheme on the supercapacitor interface for two quantum entangled bipolar charge states Φ_{+1} and Φ_{-1}. The charge distribution of two entangled excitons at the capsule interface is shown as two separate entangled electric dipoles: open circles represent hole excitations and dark circles represent electronic excitations. As a result, the charge density distribution of the entangled pair of electrons has a topological boundary with separated charges in the physical space of the material.

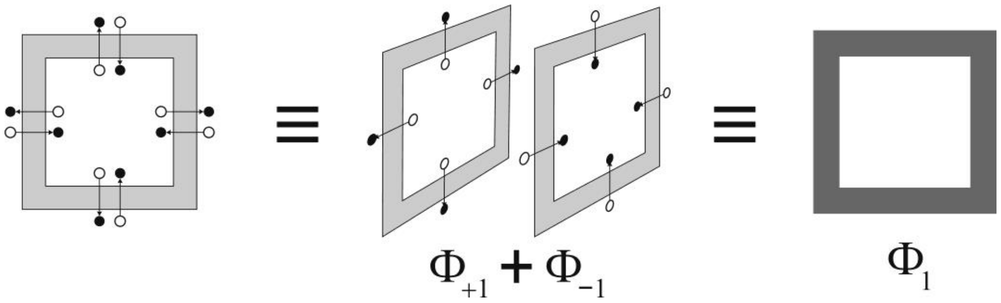

Figure 2. Diagrams of the interface capsule of NEMS in the quantum state Φ_1

During the attosecond lifetime $\delta\tau_1$, the quantum state Φ_1 of the interface capsule and the quantum state Θ_1 of its locked subsystem of nuclei and electrons are in the untangled quantum state of NEMS:

$$\Psi_1 = \Theta_1\Phi_1. \quad (4)$$

In the process of interaction of the electromechanical interface of the capsule with the electron-nuclear subsystem, secondary low energy entangled electron pair arise, which has dimensions on the order of the length of the supraatomic loggia of the capsule. Figure 3 shows that in comparison with the primary excited state Φ_1 in the excited quantum state Φ_2 a supplementary low-energy excitation of the tangled electron pair with small electron ionization I_2 and electron affinity A_2 is emerged.

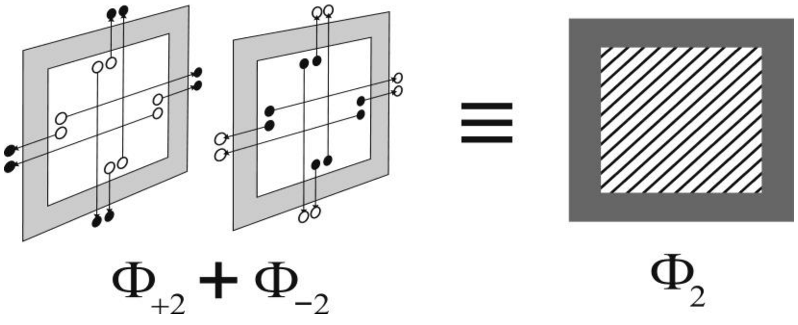

Figure 3. Diagrams of the electromechanical capsule of NEMS in the quantum state Φ_2

As it was shown in [11], the source of the excitation energy of a supplementary pair of entangled excitons on the interface is the mechanical work δA performed inside the capsule by confined nuclear-electron subsystem of the NEMS when its quantum state changes from Θ_1 to $\Theta_1 + \Theta_2$. The excitation energies of secondary electron pairs lie in the region of electronic-vibrational-rotational excitations energies of the electron-nuclear subsystem.

As a result, entanglement of the electromechanical capsule with the electronic-nuclear subsystem NEMS occurs as follows:

$$\Psi_2 = \Theta_1\Phi_1 + \Theta_2\Phi_2 . \tag{5}$$

The lifetime τ_1 of the entangled state Ψ_2 of NEMS is limited by the action of quantum thermofield fluctuations of the condensed state. As a result of such fluctuations, the NEMS spontaneously dissipates the energy of the secondary entangled pair of electrons into the medium, passing from an entangled state Ψ_2 to an untangled state $\Psi_{1'}$ Reduction occurs into the wave function Φ_1 of the capsule and a wave function $\Theta_{1'} = \Theta_1 + \Theta_2$ of the confined nuclear-electron subsystem NEMS:

$$\Psi_2 = \Theta_1\Phi_1 + \Theta_2\Phi_2 \Rightarrow \Theta_1\Phi_1 + \Theta_2\Phi_1 = (\Theta_1 + \Theta_2)\Phi_1 = \Theta_{1'}\Phi_1 = \Psi_{1'} . \tag{6}$$

The transition in time from the initial untangled state of the NEMS through the entangled state to the new untangled state, and so on, can be represented as a cycle of two-step processes:

$$\Psi_1 \overset{\delta\tau_1}{\Rightarrow} \Psi_2 \overset{\tau_1}{\Rightarrow} \Psi_{1'} \overset{\delta\tau_2}{\Rightarrow} \Psi_{2'} \overset{\tau_2}{\Rightarrow} \Psi_{1''}...... \tag{7}$$

Thus, a contextual stepwise motion of the electron-nuclear subsystem of the NEMS appears in the material. At the supra-atomic scale level, it is encapsulated in the NEMS electromechanical interface capsule formed by a subatomic entangled pair of electrons. The processes of measurement and control of the electronic-nuclear subsystem NEMS are carried out by the sensor and actuator subsystem of low-energy secondary entangled pairs of electrons. The sensory stages of pulsed attosecond measurements alternate with stages of pulsed femtosecond control.

3. Quantum dissipative infrastructure of hybrid electronic and bielectronic systems

In measurement processes, secondary low-energy entangled electron pairs dissipate the energy of the electron-nuclear subsystem of the NEMS. As a result, the process of multiplication of the subsystem of low-energy secondary entangled pairs of electrons in the surrounding dissipative medium of a condensed state occurs. They form the dissipative infrastructure of electromechanical interfaces at higher hierarchical scale levels of new quantum smart-materials [11, 13].

In view of the above, in the thermofield quantum dynamics of a condensed state, it is assumed that the material, in addition to the system of electrons, contains a subsystem of short living entangled pairs of electrons. The generalized Hilbert space of states H^{NP} of the unified electronic system is constructed by the direct product of the Hilbert space of states of *N* electrons and the Hilbert space of states of *P* entangled bielectrons:

$$\mathrm{H}^{NP} = \mathrm{H}^{Ne} \otimes \mathrm{H}^{P(2e)} . \tag{8}$$

In equation (8) the Hilbert space of states H^{Ne} of *N* electrons is represented as an antisymmetric direct product of the spaces of individual single electrons:

$$\mathrm{H}^{Ne} = Asym(\mathrm{H}_1^{1e} \otimes \mathrm{H}_2^{1e} \otimes ... \otimes \mathrm{H}_N^{1e}) . \tag{9}$$

Similarly, the Hilbert space of states $\mathrm{H}^{P(2e)}$ of *P* entangled bielectrons is represented as an antisymmetric direct product of the spaces of individual entangled electron pairs:

$$\mathrm{H}^{P(2e)} = Asym(\mathrm{H}_1^{2e} \otimes \mathrm{H}_2^{2e} \otimes ... \otimes \mathrm{H}_P^{2e}) . \tag{10}$$

The general Fock space of states H_{OES} of an open unified electronic system consisting of electrons and bielectrons is constructed as a direct sum of Hilbert spaces of states $\{\mathrm{H}^{NP}\}$ with a variable number of electrons $N = 1, 2, ...$ and a variable number of the entangled electron pairs $P = 1, 2, ...$

$$\mathrm{H}_{OES} = \oplus_N \oplus_P \mathrm{H}^{NP} . \tag{11}$$

Let us note the special status of the subatomic level of attosecond pulsed quantum processes. It is only at this basic level of the multiscale structure of the nonequilibrium condensed state that high-energy entangled electron pairs are formed. They are able to accumulate quantum electromechanical energy at the interfaces of the NEMS capsules without competing for the absorption of the energy of attosecond hard ultraviolet and soft X-ray pulses from femtochemical electronic-vibrational-rotational excitations in the material.

The uniqueness of the supra-atomic sublevel of the material structure lies in the fact that atomic-molecular processes of quantum femtochemistry and processes of quantum attophysics of nanoelectromechanical systems take place in it. There are two types of nanoscale condensed matter objects here, namely quantum nanoelectromechanical systems and quantum nanomolecular systems. They coexist “in parallel” on two-time scale sublevels: attosecond and femtosecond, respectively.

It should be taken into account that in secondary electromechanical interfaces on a scale from ten nanometers to a micrometer, the energy of tertiary entangled two-electron excitations lies within the excitation bands of conventional electronic femtochemical processes of materials and can dissipate over the degrees of freedom of electronic-vibrational-rotational excitations of the material.

Conclusions

Currently, applications of the effects of quantum entanglement, quantum contextuality and quantum dissipativity form the basis of the second quantum revolution in high technology development. This article discusses the quantum effects of entanglement, contextuality and dissipativity of subatomic and supra-atomic entangled electron pairs in a nonequilibrium condensed state. We have considered their use for the development of fundamentally new quantum subatomic nanotechnologies. In Section 1, we analyzed the prospects for the implementation of the mechanism of attosecond pulsed entanglement of pairs of subatomic electrons. In Section 2, we considered the organization of the quantum contextuality of measurement and control of nonequilibrium femtosecond electron-nuclear systems at the supra-atomic level of the condensed state of matter using subatomic entangled electron pairs. Finally, in Section 3, we discussed the prospects for applying the quantum dissipativity of the combined bosonic subsystem of primary high-energy subatomic and secondary low-energy supra-atomic entangled electron pairs in the formation of the infrastructure of new quantum smart materials.

Modern developments of quantum NEMS complement the approaches and methods for creating atomic-molecular devices. Molecular nanomachines are created by femtochemical processes using picosecond infrared and femtosecond pulsed optical radiation. The development of the direction of quantum NEMS as hybrid binary two-level quantum devices should be based on the attosecond pulsed action of hard ultraviolet radiation or soft X-ray radiation on a material. The breakthrough in this field of quantum subatomic nanotechnology of materials is delayed not only due to the lack of developed theoretical concepts and adequate computer models, but also because of the lack of precision experiments. Further research is needed.

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