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Superconductivity and its Properties: Cooper Pairs, Meissner Effect, London Moment, Gravitomagnetic and Gravitoelectric Processes

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ABSTRACT
The following properties of superconductivity are considered in this work: the creation and destruction of Cooper pairs, "mass defect", Meissner effect, London moment, gravitomagnetic and gravitoelectric processes. The conducted research has shown that for explanation of the above-mentioned properties of superconductivity it is necessary to investigate the characteristics of physical vacuum. With this aim, the following physical models of physical vacuum are analyzed in the work. The Feynman model of creating of virtual photons by quantum objects, explaining the creation and destruction of Cooper pairs, "mass defect" and partly Meissner effect. The model of physical vacuum consisting of quantum oscillators by A. Einstein and O. Stern and the model of magnetic field by L. I. Sedov. The latter two models are basic for interpretation of Meissner effect, London moment, gravitomagnetic and gravitoelectric processes.

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Introduction

In quantum mechanics, superconductivity is associated with the Bose-Einstein statistics, whereby any number of bosons can be in the lowest energy state [1]. From the point of view of classical mechanics, superconductivity is a result of motion of electrons in a medium without viscosity. Viscosity is determined by magnetic, gravitational and electric interactions of electrons (including the electric dipole interaction of virtual photons created by these electrons, according to theory by Feynman).

The production of Cooper pairs with zero total electric dipole moment of virtual photons created by electrons of each pair and with zero total spin of these electrons (consequently, with zero total spin magnetic moment of electrons) decreases electric and magnetic interactions between Cooper pairs of electrons. However, the reduction of viscosity of electron medium and **the emergence of superconducting properties in this way** are not the only characteristics of the of superconductor.

Except for zero electrical resistance, superconductor is characterized by the following properties:
"mass defect"; effect of Meissner; moment of London; gravitomagnetic and gravitoelectric processes.

The above-mentioned characteristics of superconductor are determined by the properties of physical vacuum. So, this work consists of two parts. The first part is devoted to the consideration of the properties of physical vacuum defining the above-listed phenomena. In the second part these phenomena are analyzed.

I. Brief Characteristics of Some Models of Physical Vacuum

1.1. The model of physical vacuum consisting of quantum oscillators

A. Einstein and O. Stern in 1913, using the formula derived by Planck [2] for the energy ε_o of the atomic oscillator vibrating with frequency ν: $\varepsilon_o = h\nu/2 + h\nu/\left(\exp\left(h\nu/(kT)\right)-1\right)$, published a paper [3] in which they classified $h\nu/2$ as "residual energy" (later, "residual energy" was called "zero-point energy") that all atomic oscillators have at absolute zero. In quantum field theory, a physical vacuum free from magnetic and electric fields (without regard to gravitational energy) became defined not as an empty space but as the ground state of a field that consists of oscillators with zero-point energy [4]. These oscillators have no generally accepted name but, in this work, they are called quantum oscillators (from now on, the abbreviation "*qo*" will be used). The mass m_{qo} is connected with the "residual energy":

$$m_{qo} = h\nu/\left(2c^2\right). \tag{1}$$

The electrical polarization of physical vacuum in electric field indicates that a quantum oscillator consists of electric oppositely charged particles: ("+particles" and "-particles").

Physical effects exist which are impossible to explain without ascribing an intrinsic degree of freedom to the physical vacuum, namely the spin. For example, a photon has a spin angular momentum and so-called orbital angular momentum [5]; at the same time, in the photon's emission by an atom only the orbital angular momentum is transferred to the photon in most atomic transitions. Another example, in the photon's emission by a free-moving electron at the speed higher than the speed of light (the Cherenkov effect [6]), the electron conserves its own spin angular momentum. Consequently, the principle of conservation of angular momentum only holds at the emission of the photons if quantum oscillators constituting the physical vacuum have spin $\mathbf{S}_{qo}$.

I.2. Model of magnetic field

Continuing the analogy between "*electro-magnetism and hydrodynamics.*" proposed by Maxwell [7], L. I. Sedov pointed that magnetic phenomena might be due to the motion of a medium simulated by ideal incompressible liquid with positive density and negative pressure (characterized by "omniradial tensions") that is described at the stationary motion (without regard to gravitational forces) by the following equation [8]:

$$\rho y^2/2 - p = const, \tag{2}$$

where ρ, *y*, and *p* are, respectively, the density, speed, and pressure, of the medium. Based on the above-mentioned characteristics of quantum oscillators the following assumption can be made: a physical vacuum consisting of quantum oscillators with zero-point energy could be such a medium. Let us consider this in more detail.

1) Mass m_{qo}, Eq. (1), may create positive density ρ of the physical vacuum.
2) From the dissipation-free motion of celestial bodies, such as the solar system's planets, it follows that the shear viscosity in a physical vacuum can be negligible.
3) The emergence of the electric polarization of spin vortices (photons, virtual photons) arising in physical vacuum means the existence of a repulsive force between the oppositely charged particles that constitute the quantum oscillators forming vortices, thereby compensating the attractive Coulomb force between these charges. The existence of this type of repulsive force can be treated as the existence of "omniradial" tensions

inside spin vortices. In terms of hydrodynamics, it means that the physical vacuum consisting of quantum oscillators, as a continuous medium, can be regarded as a medium with negative pressure.

4) The vortices in the physical vacuum consisting of quantum oscillators can terminate in the bulk of this vacuum due to the complete transfer of the angular momenta connected with vortices to their spins.

As shown in [8] and follows from Eq. (2), magnetic induction **B** is related to velocity **y** of motion of the physical vacuum consisting of quantum oscillators by the expression:

$$\mathbf{B} = \mathbf{y}\sqrt{4\pi\rho}\,. \tag{3}$$

1.3. Model (hypothesis) of virtual photons

R. Feynman in 1949 developed the diagram of force fields in which any force interaction is performed by the virtual particles created by interacting objects [9]; for example, electric and magnetic interactions are accomplished by so-called virtual photons consisting of a pair of electric oppositely charged virtual particles. The properties of virtual photons were similar to those of photons performing the propagation of the electromagnetic oscillations as well, in particular, both have a precessing spin and electric dipole moment, consequently, they are spin vortices in the physical vacuum consisting of quantum oscillators.

In 2020, the investigation by H. Li and others [10] was conducted the supporting hypothesis of Feynman: "We report the quantized superfluid vortex filaments induced by the axial flow effect". Really, the superfluid medium in investigation by H. Li characterized by intrinsic angular momentum is similar to the physical vacuum characterized by "zero-point energy". Thus, it follows from the investigation by H. Li that the motion (at velocity **u**) of quantum object can be followed by "quantized superfluid vortex filaments", in particular, by spin vortex (virtual photon).

Consequently, the following relation exists: $\mathbf{u} \sim \boldsymbol{\omega}_V$. According to the updated experimental data [11]:

$$\boldsymbol{\omega}_V \uparrow\uparrow \eta\mathbf{u}\,, \tag{4}$$

$$\eta = \begin{cases} 1, & \textit{for positively charged quantum object} \\ -1, & \textit{for negatively charged quantum object} \end{cases}; \tag{5}$$

One of the main properties of spin vortex is the precession motion (with frequency $\boldsymbol{\omega}_V$) of its spin $\mathbf{S}_V$ and according to the S. J. Barnet effect [12] and the properties of gyroscopes [8]:

$$\mathbf{M} = \boldsymbol{\omega}_V \times \mathbf{S}_V\,. \tag{6}$$

where M is moment causing precession of $\mathbf{S}_V$.

The forming of mass and electric dipole moment in a virtual photon

As virtual photons are spin vortices in the physical vacuum consisting of quantum oscillators, the characteristics of these spin vortices are determined by characteristics of the quantum oscillators. It means that virtual photon spin, $\mathbf{S}_V$, consists of spins $\mathbf{S}_{qo}$ of the quantum oscillators constituting the virtual photon:

$$\mathbf{S}_V = \sum_{\substack{virtual\\photon}} \mathbf{S}_{qo}\,. \tag{7}$$

At arising of spin vortex, according to the S. J. Barnet effect, reorientation of spins $\mathbf{S}_{qo}$ of quantum oscillators constituting the arising spin vortex takes place. That is, the change in the projection of $\mathbf{S}_{qo}$ on direction $\mathbf{S}_V$ takes place:

$$\partial\left(\mathbf{S}_{qo}\right)_{\mathbf{S}_V} / \partial t \neq 0\,. \tag{8}$$

Due to the law of conservation of angular momentum, a change in the angular momentum results in emergence of the processes and forces compensating this change. In the work [13], the existence of the force ("force of inertia") compensating the change in the angular momentum is shown. In this case the force (denote it $\mathbf{F}_{qo}$) is represented (with taking into account Eq. (8)) in the form of:

$$\mathbf{F}_{qo} = -\eta_{qo}\mathbf{S}_v \left| \gamma_s \partial \left(\mathbf{S}_{qo}\right)_{\mathbf{S}_v} / \partial t \right| \quad (9)$$

where γ_s is a factor of proportionality,

$$\eta_{qo} = \begin{cases} 1, \textit{for positivly charged particle} \\ (\text{"+" particle}) \textit{ of quantum oscillator}; \\ -1, \textit{for negativly charged particle} \\ (\text{"−" particle}) \textit{ of quantum oscillator}. \end{cases} \quad (10)$$

According to Eqs (9) - (10). the velocity of “+particle” is oriented as $\boldsymbol{\upsilon}_+ \uparrow\downarrow \boldsymbol{\omega}_\mathbf{v}$; the velocity of “-particle” ($\boldsymbol{\upsilon}_-$) is oriented as $\boldsymbol{\upsilon}_- \uparrow\uparrow \boldsymbol{\omega}_\mathbf{v}$. Thus, the velocity of charged particles constituting the quantum oscillators in general is determined as:

$$\boldsymbol{\upsilon} \uparrow\downarrow \eta_{qo}\boldsymbol{\omega}_\mathbf{v}. \quad (11)$$

Schematic image of forming electric dipole moment $\mathbf{d}_v$ with taking into account Eqs (4)-(6) and (11), and the action of electric field of quantum object on electric dipole moment $\mathbf{d}_v$ created by this object is presented in Figure 1.

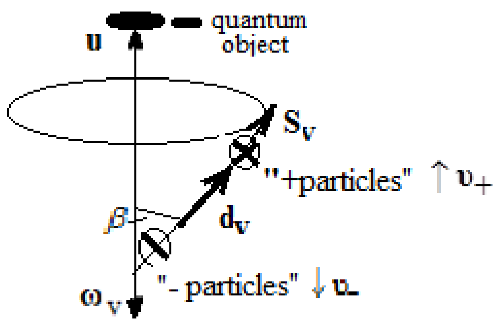

Figure 1: Schematic image of structure of electric dipole moment $\mathbf{d}_v$. “*+ particles”* is an accumulation area of positively charged particles, with velocity $\boldsymbol{\upsilon}_+$, constituting the quantum oscillators of physical vacuum; “*-particles”* is an accumulation area of negatively charged particles, with velocity $\boldsymbol{\upsilon}_-$, constituting the quantum oscillators of physical vacuum. β is the angle of deflection.

$$\sin\beta = u/c. \quad (12)$$

where c is the speed of light.

It follows from Eqs (9)-(10) and Figure 1:

$$\mathbf{d}_v \uparrow\uparrow \mathbf{S}_v. \quad (13)$$

The determination of electric dipole moment of spin vortex

By definition, d_v is determined by size δ_v of virtual photon and electric charge q_v of virtual particle constituting the virtual photon:

$$d_v = q_v\delta_v. \quad (14)$$

In Feynman’s model, the virtual photon is created in the area whose size equals wavelength $\lambda\!\!\!^{-}_q$ of the wave function of quantum object creating this virtual photon. In quantum mechanics, $\lambda\!\!\!^{-}_q$ is determined by momentum p_q of quantum object [14]: $\lambda\!\!\!^{-}_q = \hbar/p_q$, thus, from Eq. (14) it follows:

$$d_v = q_v\lambda\!\!\!^{-}_q = q_v\hbar/\lambda\!\!\!^{-}_q. \quad (15)$$

Based on the results of experiments conducted by Kaufmann [15] on the deflection of beta-rays emitted by radium, which showed that the mass of electron m_e is purely of an electromagnetic nature, we assume that the same is valid for the virtual particles that constitute the virtual photon with mass m_v: that is, the following holds: $e/m_e = 2q_v/m_v$ (e is the electric charge of electron).

From the latter expression, we obtain the expression for q_v:

$$q_v = em_v/\left(2m_e\right). \quad (16)$$

As, according to Feynman’s hypothesis, the properties of virtual photon are similar to the properties of photon, the mass of virtual photon m_v will be defined similar to kinetic mass of photon: $m_{ph} = U_{ph}/c^2$, where U_{ph} is photon energy, c is the speed of light. Consequently, the mass of virtual photon will be defined as:

$$m_v = U_q/c^2, \quad (17)$$

where U_q is the energy of quantum object creating the virtual photon. Solving together Eqs (15)-(17) and using the expression for magneton of Bohr $\mu_B = e\hbar/(2cm_e)$, we obtain:

$$d_v = \mu_B U_q / (p_q c). \tag{18}$$

If energy U_q of quantum object (with mass m_q and speed u) equals kinetic energy:

$$U_q = m_q u^2 / 2 \tag{19}$$

then using expression for momentum $p_q = m_q u$ the Eq. (18) can be presented as:

$$d_v = \mu_B u / (2c). \tag{20}$$

2. The Properties of Superconductor

2.1. The formation of Cooper pairs

Let us prove that formation of Cooper pairs of electrons can be a consequence of electric dipole-dipole interaction of virtual photons created by these electrons. It follows from experiments that Cooper pairs of most superconductors consist of electrons in the *s*-state in which the total spin of electron pair is equal to zero and the velocities of electrons in the pair (respectively $\mathbf{u}_1$ and $\mathbf{u}_2$) are oriented as:

$$\mathbf{u}_1 \uparrow\downarrow \mathbf{u}_2. \tag{21}$$

According to Figure 1 the projections on $\mathbf{u}_1 \uparrow\downarrow \mathbf{u}_2$ of electric dipole moments of virtual particles created by electrons of the pair (respectively $(\mathbf{d}_v)_1$ and $(\mathbf{d}_v)_2$) are oriented as: $(\mathbf{d}_v)_1 \uparrow\downarrow (\mathbf{d}_v)_2$ (see Figure **2**). In this case, according to [16], attractive force F_{va} acts between virtual photons.

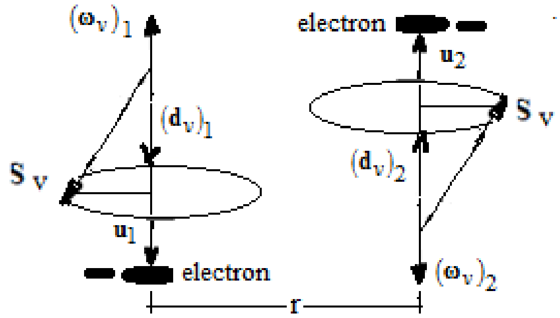

Figure 2: The schematic image of virtual photons created by pair of electrons. r is distance between electrons; $(\boldsymbol{\omega}_v)_1$ and $(\boldsymbol{\omega}_v)_2$ are the frequencies of precession of spins $\mathbf{S}_v$, $(\mathbf{d}_v)_1$ and $(\mathbf{d}_v)_2$ are electric dipole moments, $\mathbf{u}_1$ and $\mathbf{u}_2$ are the velocities of electrons**.**

If the distance r between virtual photons created by electrons significantly greater than the size of electric dipoles $\lambda\!\!\!^{-}_q$ (see Eq. (15)), that is: $r >> \lambda\!\!\!^{-}_q$ the attractive force F_{va} acting between these virtual photons is determined by expression [16]:

$$F_{va} = 3(d_v)_1 (d_v)_2 / r^4. \tag{22}$$

Let us determine distance r_c between electrons at which attractive force F_{va} between them, determined by Eq. (22), is equal to repulsive Coulomb force F_e between them.

$$F_{va} = F_e = e^2 / r^2, \tag{23}$$

where e is the electron charge. From Eqs (18)-(20) and (22)-(23) we obtain (in measurement system CGS):

$$r_c = \sqrt{3}\mu_B u / (2ce). \tag{24}$$

2.2. The "mass defect". Effect of Meissner

The mass defect – a decrease of full mass of virtual photons created by electrons when they form a Cooper pair.

Let us compare the value r_c with wavelength $\lambda\!\!\!^{-}$ of electron determined as: $\lambda\!\!\!^{-} = \hbar/(m_e u)$ [14]. With this aim, let us estimate ratio $r_c/\lambda\!\!\!^{-}$ using expression (24):

$$r_c/\lambda\!\!\!^{-} = \sqrt{3}\mu_B u^2 m_e / 2c\hbar e. \quad (25)$$

As the value of energy of electron creating a Cooper pair equals approximately the value of Fermi energy ε_F [17], the speed u of electron is determined by expression $u \approx \sqrt{2\varepsilon_F/m_e}$. For metal, the average value of the speed may be accepted as [17-18]:

$$u \approx 10^6 m/s. \quad (26)$$

Using in Eq. (25) the values of all constants, we obtain the following ratio: $r_c/\lambda\!\!\!^{-} \approx 10^{-6}$. As $\lambda\!\!\!^{-}$, according to Feynman hypothesis, determines the size of virtual photon, the obtained value $r_c/\lambda\!\!\!^{-}$ means the partial spatial overlap of virtual photons created by electrons of Cooper pairs (see Figure 3).

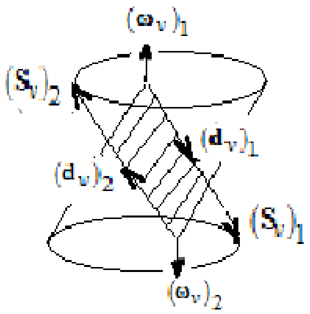

Figure 3: The schematic image of partial spatial overlap of virtual photons created by pair of electrons; $(\boldsymbol{\omega}_v)_1$ and $(\boldsymbol{\omega}_v)_2$ are the frequencies of precession of spins $(\mathbf{S}_v)_1$ and $(\mathbf{S}_v)_2$; $(\mathbf{d}_v)_1$ and $(\mathbf{d}_v)_2$ are electric dipole moments. The shaded area is a "vortex free area"; in this area the physical vacuum has no quantum oscillators.

According to Eq. (1) and Figures 1 and 3, in the area of partial spatial overlap the quantum oscillators mass will be missing and this area can be called "vortex free area". Thus, the total mass of virtual photons created by electrons of a Cooper pair becomes less and this difference is called "mass defect" (Δm_v). This conclusion coincides with experimental data: if a substance is converted into superconducting state, its weight will decrease [17-18].

The maximum mass defect $(\Delta m_v)_{\max}$ equals total mass of virtual photons created by electrons of a Cooper pair. Then it follows from Eq. (19) and (26) that

$$(\Delta m_v)_{\max} = m_e u^2/c^2$$
$$= 0.911 \cdot 10^{-27} \cdot 10^{16}/9 \cdot 10^{20} \approx 10^{-35} kg.$$

In this case, the disappearance of a Cooper pair takes place. (At present, the mass defect of the most used superconductor has an order of magnitude $\sim 10^{-39} kg$ [19]).

Effect of Meissner – excluding of magnetic field lines from a superconductor, when it is below its critical temperature [17-18].

The existence of "vortex free area" means the existence of area where there are no quantum oscillators and, consequently, the equations (2) and (3) are invalid and magnetic interaction cannot exist in this area.

If only the partial spatial overlap of the virtual photons created by electrons of Cooper pairs takes place, the magnetic field lines can penetrate into superconductor in the form of vortex line. For example, "the vortices of Abrikosov" are observed in superconductors of the second type. The superconductors of the second type have areas characterized both by superconducting and nonsuperconducting properties and magnetic field can penetrate in the superconductor to a shallow depth [19].

2.3. The London moment

Rotating superconductor generates a magnetic field aligned with the axis of rotation [20], see Figure 4.

The field is measured outside the superconductor. At the same time, the external magnetic and electric fields are absent. The phenomenon is called "London moment". London moment does not depend on the magnetic permeability, μ_0, of vacuum which is usually common to all classical magnetic phenomena. (London moment is generated in addition to the usual magnetic field in standard Maxwell theory).

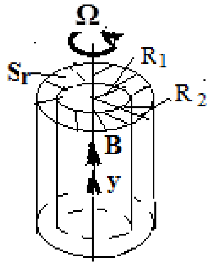

Figure 4: Schematic image of setup generating magnetic moment of London. **Ω** is angular velocity of rotation of superconductor; **B** is magnetic induction; **y** is the velocity of a physical vacuum consisting of QOs; Sr is superconductor located between cylinders with radii R_1 and R_2.

In the area of rotation (inside of cylinder with radius R_1), physical vacuum consists of quantum oscillators having spin $\mathbf{S}_{qo}$. Due to the Barnett effect the orientation of quantum oscillators' spins arises in this area. This change in the property of physical vacuum filled with quantum oscillators results in a change of pressure p in this vacuum as continuum medium. Thus, gradient pressure emerges between the physical vacuum in the cylinder with radius R_1 and the rest physical vacuum. Then, according to Eq. (2), the motion of the physical vacuum (filled with quantum oscillators) with velocity **y** oriented along **Ω** arise: $\mathbf{y} \sim grad p_{\mathbf{\Omega}}$. According to Eq. (3), the magnetic field $\mathbf{B} \uparrow\uparrow \mathbf{\Omega}$ emerges.

Note: It is possible that the inner wall-layer (radius R_1) of superconductor creates a boundary condition in the area of emergence of magnetic field.

2.4. The gravitomagnetic moment of London

Except for London moment, gravitomagnetic fields created by an accelerated rotation (increasing number of revolutions) of superconductor in the region close to the superconductor were found (Figure 5) [21]. This phenomenon was discovered experimentally and was called "London gravitomagnetic moment". As opposed to London moment, gravitomagnetic field is characterized not only by magnetic phenomena but by emergence of mass as well.

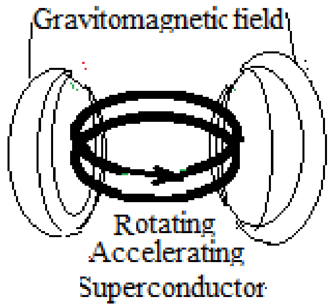

Figure 5: Schematic image of gravitomagnetic field created by rotating and accelerating superconductor.

The rotation of superconductor means the appearance of magnetic field similar to the emergence of the London moment. The acceleration of rotation of superconductor results, according to Eqs. (8) - (11), in occurrence of force creating mass in arising spin vortices. Therefore, the resulting gravitational field turns out to be directly proportional to the applied angular acceleration of the superconductor.

2.5. The gravitoelectric field created by the gravitomagnetic field changing over time

If gravitomagnetic field changes over time, the gravitoelectric field appears (see Figure 6) [22].

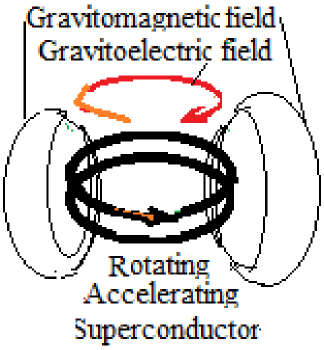

Figure 6: Schematic image of gravitomagnetic and gravitoeletric fields created by rotating (with acceleration) superconductor. And the gravitoeletric field arises if the gravitomagnetic field changes with time.

The magnetic component **B** of gravitomagnetic field can be transformed into an electric component **E** due to the action of law of Maxwell: $curl\mathbf{E}\cdot c = -\partial\mathbf{B}/\partial t$ where c is the speed of light, t is time.

3. The destruction of superconducting properties

The destruction of superconducting properties will take place at breaking Cooper pairs**.** One of the methods of breaking Cooper pairs is the generation of repulsive force between virtual particles created by the electrons of Cooper pair. According to Eqs (4)-(6), (13) and (22), this may be fulfilled by motion of the pair in one direction: for example, at arising of electric current or due to an increase in temperature. In the latter case, the speed of electron in Cooper pair u is related to temperature T as $u = \sqrt{2kT/m_e}$ (m_e is electron mass, k is Boltzmann constant). If we assume that a Cooper pair takes part only in the thermal motion, repulsive force F_r between electrons of Cooper pair, according to Eqs (4)-(6), (13), (20) and (22), is determined as: $F_r = \mu_B^2 kT/\left(2m_e c^2 r^4\right)$.

Results and Discussion

1. The Cooper pair in superconductor emerges due to action of attractive force between virtual photons created by electrons constituting the Cooper pair.
2. The "mass defect" of the Cooper pair and effect of Meissner (rejection of magnetic field lines from a superconductor) take place due to changes in properties of the physical vacuum, in particular, the disappearance of quantum oscillators in the area of the Cooper pair.
3. The generation of magnetic field by rotating superconductor (London moment) can be explained by a change in the properties of physical vacuum in the area of rotation due to action of Barnett effect on spins of quantum oscillators constituting the physical vacuum.
4. The generation of magnetic and gravitational fields (gravitomagnetic field) can be explained, first, by a change in the properties of physical vacuum in the area of rotation due to action of Barnett effect on spins of quantum oscillators; secondly, by the emergence of a force causing collapses of similarly charged parts of quantum oscillators.
5. The generation of the gravitoelectric field as a result in a change in time of gravitomagnetic field is explained by action of Maxwell's law connecting electric and magnetic fields changing in time.
6. The destruction of the superconducting properties will take place at the destruction of Cooper pairs**.** One of the methods of destruction of Cooper pairs is the generation of repulsive force between virtual particles created by the electrons of the Cooper pair.

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