Chapter 1

The Process of Transfer of Angular Momentum. Spin Supercurrent

The first works introducing the process of transfer of angular momentum in descriptions of physical phenomena were works by J. C. Maxwell describing a model of luminiferous ether in 1861-1873 [2,3]. In hundred years, the investigation of process of transfer of angular momentum was continued (with taking into account the quantum object characteristic discovered in the 20th century - spin) by M. Vuorio [4], in his experiments this process was called "long transport of spin polarization". In the following years the process was studied in experiments with superfluid ^{3}He-B by A. Borovic-Romanov, Yu. Bunkov, V. Dmitriev, I. Fomin et al [5,6,7]; in the latter investigations the process of transfer of angular momentum is called "spin supercurrent".

1.1. The Process of Transfer of Angular Momentum in the Maxwell Model of Luminiferous Ether

In the Maxwell model of luminiferous ether, the latter consists of two phases. (Below the citations from the Maxwell work [2] are written in italic type). According to the model, the properties of the first phase of luminiferous ether determine the magnetic interaction and had to explain the results of Faraday's experiments with magnetic field and the properties of light. In this conception the first phase had to have the properties "*of ordinary matter*" ([2], p.345), described by Newton's equations. Besides, the first phase had to have vorticity, and the "*velocity of the circumference of each vortex must be proportional to the intensity of the magnetic force*" ([2], p.282).

In contrast to the first phase, Maxwell supposed that the substance of the second phase is "*not a substance at all, or in what way it differs from matter*" ([2], p.282). One of the tasks of the second phase of luminiferous ether, according to Maxwell, was to provide synchronization of the rolling of vortices of the first phase and "*transmit the motion of rotation to them, till at last all the vortices in the medium are set in motion with such velocities of rotation*" ([2], p.347). Concerning the properties of this process, Maxwell wrote, "*the angular velocity must be the same throughout each vortex*" and "*are maintained for an indefinite time without any expenditure of energy*" ([2], p.346). Thus, Maxwell supposed the existence of a dissipation-free process in the second phase accomplishing the transfer of angular momentum between vortices of the first phase.

Maxwell does not define the speed y_{tam} of angular momentum transfer, but as this process determines the formation of magnetic component of electromagnetic oscillations, the speed y_{tam} must be no less than the speed of spreading these oscillations (c). Consequently, it can hold:

$$y_{tam} \geq c . \tag{1.1}$$

Maxwell deduced an equation characterizing the process of transfer of angular momentum as follows: "..*let the circumferential velocity of a vortex, multiplied by the three direction-cosines of its axis respectively, be* α , β , γ . *Let l, m, n be the direction-cosines of the normal to any part of the surface of this vortex, the outside of the surface being regarded positive. Then the components of the velocity of the particles of the vortex at this part of its surface will be* $n\beta - m\gamma$ *(parallel to x),* $l\gamma - n\alpha$ *(parallel to y),* $m\alpha - l\beta$ *(parallel to z).*

If this portion of the surface be in contact with another vortex whose velocities are α' , β' , γ' , *then* a *layer of very small particles placed between them will have* a *velocity which will be the mean of the superficial velocities of the vortices which they separate, so that if* **u***is the velocity of the particles in the direction of* **x,**

$$u = \frac{1}{2} m\left(\gamma' - \gamma\right) - \frac{1}{2} n\left(\beta' - \beta\right), \tag{1.2}$$

since the normal to the second vortex is in the opposite direction to that of the first." ([2], pp.283-284).

It should be noted that as variables α , β, and γ (α', β', and γ', as well) determine the circumferential velocity of the vortices, at equal diameters of vortices the differences $\left(\alpha' - \alpha\right)$, $\left(\beta' - \beta\right)$ and $\left(\gamma' - \gamma\right)$ determine the difference in angular velocities of vortices between which the process of transfer of angular momentum emerges.

Thus, Eq. (1.2) can determine the process emerging in the second phase of Maxwell's luminiferous ether that tends to equalize the angular velocities of vortices between which it emerges. This process is characterized by the absence of "*any expenditure of energy*". The process of transfer of angular momentum in Maxwell's model is not only dissipation-free but inertia-free as well [13].

In the following Section the properties of the process of angular momentum's transfer (now referred to as "spin supercurrent") observed in contemporary investigations will be considered.

1.2. The Properties of Spin Supercurrent

1.2.1. Spin vortices in the physical vacuum

The process of transfer of angular momentum introduced by Maxwell emerges between the vortices whose motion determines magnetic phenomena. That is, this process is spreading in the medium "finer" than molecular one. If spin supercurrent and Maxwell's process of angular momentum transfer are the same process, it can be supposed that spin supercurrent emerges between spin vortices created by quantum objects in the physical vacuum. The spin vortex with zero-rest mass is called "photon"; the spin vortex created by a quantum object having nonzero rest mass is called "virtual photon" [10].

Let us consider the characteristics of these spin vortices.

Photon.

The data of the three-photon annihilation of electron and positron with a total spin equal to one (orthopositronium) [14] suggest that the spin $\mathbf{S}_{ph}$ of any photon is directed transverse to the velocity of light **c**: that is, $\mathbf{S}_{ph} \perp \mathbf{c}$. The photon has the transverse electric polarization, as well, that is $\mathbf{E}_{ph} \perp \mathbf{c}$, and it was shown in work by L. Bodyreva [10] that:

$$\mathbf{E}_{ph} \uparrow\downarrow \mathbf{S}_{ph} . \tag{1.3}$$

A photon in a pure state is a circular-polarized photon [15]. This means that the electric component $\mathbf{E}_{ph}$ of the photon and consequently its spin $\mathbf{S}_{ph}$ perform a precession motion with the frequency ω_{ph} of the photon, determined by photon's energy U_{ph}:

$$\omega_{ph} = U_{ph} / h . \tag{1.4}$$

Virtual photon.

According to Feynman's model [8], a quantum object which is a singularity in electric or magnetic fields (electric charge or/and magnetic dipole) creates a pair of oppositely charged electric particles, the so-called virtual particles. This pair is also called a "virtual photon" since it transfers electric and magnetic interactions; like a photon the virtual photon has a precessing spin. The connections between characteristics of virtual photon (between spin $\mathbf{S}_v$ and electric component $\mathbf{E}_v$, and between frequency of precession ω_v and energy U_q of the quantum object creating the virtual photon) are similar to the connections between analogous characteristics of photon (between its spin $\mathbf{S}_{ph}$ and electric component $\mathbf{E}_{ph}$, and between frequency ω_{ph} and energy U_{ph}, see Eqs [1.3]-[1.4]):

$$\mathbf{E}_v \uparrow\downarrow \mathbf{S}_v, \tag{1.5}$$

$$\omega_v = U_q / \hbar . \tag{1.6}$$

As, according to Feynman’s model, the virtual photon is an electric dipole, its electric component $\mathbf{E}_v$ is an electric field created by the electric dipole. Consequently, taking into account Condition (1.5), the following holds for electric dipole moment $\mathbf{d}_v$ of virtual photon:

$$\mathbf{d}_v \uparrow\uparrow \mathbf{S}_v . \tag{1.7}$$

The angle of deflection β_v of virtual photon, angle between frequency of precession ($\mathbf{-\omega}_v$) and spin ($\mathbf{S}_v$), according to [10], is determined as:

$$\beta_v = \arcsin\left(u / c\right), \tag{1.8}$$

where u is the speed of quantum object creating the virtual photon. It follows from (1.8) that at $u \to c$ $\mathbf{S}_v \perp \mathbf{u}$, that is a virtual photon must be transformed into a “real” photon. The existence of effect by Cherenkov (the photon’s emission by a free-moving electron at the speed equal to the speed of light) proves the accuracy of expression (1.8).

From the physical point of view, the creation of virtual particle by a quantum object can be a consequence of interaction of the moving quantum object’s spin with the physical vacuum which can be performed with participation of Barnett’s effect [17]. The orientation of precession frequency $\boldsymbol{\omega}_v$ of virtual photon’s spin $\mathbf{S}_v$ is associated with the orientation of velocity $\mathbf{u}$ of the quantum object creating this virtual photon [16] as:

$$\boldsymbol{\omega}_v \uparrow\uparrow q\mathbf{u}, \tag{1.9}$$

where factor q reflects the action of electric field of the quantum object on the virtual photon as on an electric dipole; q=1 for the positively charged quantum object; q=-1 for the negatively charged quantum object.

If the speed of quantum object is much less than the speed of light, then, according to Eq. (1.8), $\beta_v \to 0$, and, consequently: $\boldsymbol{\omega}_v \uparrow\downarrow \mathbf{S}_v$, or, taking into account Eq. (1.9) and [10],

$$\mathbf{S}_v \uparrow\downarrow \mathbf{S}_q . \tag{1.10}$$

The size δ_v of virtual photon (as an electric dipole) equals the wavelength of quantum object creating the virtual photon:

$$\delta_v \sim \lambda_q \tag{1.11}$$

1.2.2. The properties of spin supercurrent

Let us consider the features of spin supercurrent emerging between virtual photons created by quantum objects basing on the properties of spin supercurrent observed in experiments with superfluid ^{3}He-B.

1) The value of spin supercurrent is determined by the following characteristics of precession of spins: the mutual orientation of their frequencies of precession, the precession angles (phases) α and the deflection angles β. For example, the value of a spin supercurrent I_{SSZ} in the direction of orientation (axis **z**) of the precession frequencies of the ^{3}He atoms' spins in superfluid ^{3}He-B is determined to be $I_{SSZ} = -g_1 \partial\alpha / \partial \mathrm{z} - g_2 \partial\beta / \partial \mathrm{z}$, where g_1 and g_2 are coefficients depending on β and the properties of the superfluid [7].

Note. The spin supercurrent is missing if the mutual orientation of the precession frequencies is crossover.

Based on the above written equation for I_{SSZ} and introducing coefficients $b_1 > 0$ and $b_2 > 0$ associated with coefficients g_1 and g_2, the value of spin supercurrent I_{SSZ} between two virtual photons in the direction of orientation of their precession frequencies $\boldsymbol{\omega}_1$ and $\boldsymbol{\omega}_2$ (along axis **z)** can be described by the expression:

$$I_{SSZ} = -b_1 \left(\alpha_2 - \alpha_1 \right) - b_2 \left(\beta_2 - \beta_1 \right), \tag{1.12}$$

where α_1 and α_2 are the angles of precession, β_1 and β_2 are the angles of deflection of interacting virtual photons. Expression (1.12) is similar to expression (1.2) obtained in Maxwell's model.

The schematic image of the characteristics of the considered virtual photons is presented in Figure 1.1: $\boldsymbol{\omega}_1$ and $\boldsymbol{\omega}_2$ are the precession frequencies oriented along axis $\mathbf{z}$; $\mathbf{S}_1$ and $\mathbf{S}_2$ are spins; r.l. is a reference line; $\mathbf{E}_1$ and $\mathbf{E}_2$ are electric components; $\mathbf{d}_1$ and $\mathbf{d}_2$ are electric dipole moments.

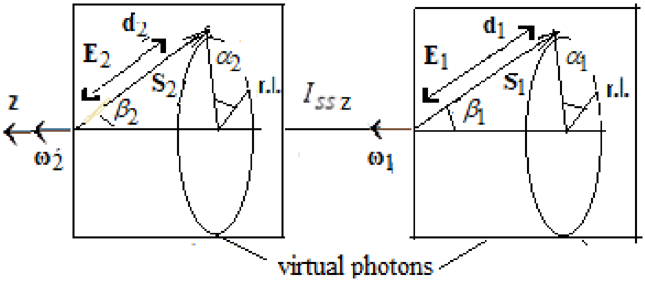

Figure 1.1. The characteristics of virtual photons. α_1 and α_2 are the angles of precession; β_1 and β_2 are the angles of deflection; $\boldsymbol{\omega}_1$ and $\boldsymbol{\omega}_2$ are the precession frequencies oriented along axis $\mathbf{z}$; $\mathbf{S}_1$ and $\mathbf{S}_2$ are spins; r.l. is a reference line; $\mathbf{E}_1$ and $\mathbf{E}_2$ are electric components; $\mathbf{d}_1$ and $\mathbf{d}_2$ are electric dipole moments; I_{ssz} is a spin supercurrent.

2) The spin supercurrent equalizing the values of characteristics of quantum objects constituting the quantum liquid can be considered as a process providing the possibility of describing the medium by a single wave function. From that it follows, according to postulates of quantum mechanics, that the speed of spin supercurrent must be infinite. There is no contradiction with Special Relativity since spin supercurrent is *an inertia-free process* (is not accompanied by emergence of mass); while the Special Relativity postulates the speed limit only for an inertial process [11]: “In any inertial frame of reference, light propagates isotropically, independent of the motion of its source, and the speed of light is equal to absolute constant *c*.”

Thus, the speed of the spin supercurrent y_{ss} can be greater than the speed of light *c*, which is in accordance with Eq. (1.1) in Maxwell’s model.

$$y_{ss} > c \,. \tag{1.13}$$

The absence of mass means the absence of energy connected with it. This property of spin supercurrent is in accordance with the conclusion by Maxwell: the transfer on angular momentum is characterized by the absence of “*any expenditure of energy*”.

3) Spin supercurrent tends to equalize the respective characteristics of the spins of interacting virtual photons, that is, the following inequalities take place:

$$\left|\alpha_1 - \alpha_2\right| \geq \left|\alpha_1^{'} - \alpha_2^{'}\right|, \tag{1.14}$$

$$\left|\beta_1 - \beta_2\right| \geq \left|\beta_1^{'} - \beta_2^{'}\right|, \tag{1.15}$$

where $a_1^{'}$ and $a_2^{'}$ are the values of the precession angles of the virtual photons' spins after the action of spin supercurrent; $\beta_1^{'}$ and $\beta_2^{'}$ are the values of the deflection angles of the virtual photons' spins after the action of spin supercurrent.

4) As a result of the spin supercurrent action, a change in the spin precession frequencies of interacting virtual photons can take place. Let us prove it using the example of two virtual photons in Fig. 1.1. Assume that before the action of spin supercurrent the precession angles a_1 and α_2 of the spins of these structures are associated with the respective precession frequencies ω_1 and ω_2 (ω_1 and ω_2 are independent of time *t*) as follows: $\alpha_1 = \omega_1 t + \alpha_{01}$ and $\alpha_2 = \omega_2 t + \alpha_{02}$, where α_{01} and α_{02} are the values of the precession angles at $t = 0$. If $\alpha_{01} = \alpha_{02} = 0$ then:

$$\alpha_1 = \omega_1 t, \tag{1.16}$$

$$\alpha_2 = \omega_2 t. \tag{1.17}$$

After the action of spin supercurrent, according to Condition (1.14) and Eqs (1.16)-(1.17), the following inequality can take place:

$$\left|\omega_2 - \omega_1\right| \geq \left|\omega_2^{'} - \omega_1^{'}\right|, \tag{1.18}$$

where $\omega_1^{'}$ and $\omega_2^{'}$ are the precession frequencies of spins of interacting virtual photons after the action of spin supercurrent.

5) At a definite difference $\Delta\alpha_c = \alpha_1 - \alpha_2$ in the precession phases of the spins of interacting virtual photons, a precession phase slippage (drop) takes place. The critical spin supercurrent $\left(I_{ssz}\right)^c$ corresponds to the value $\Delta\alpha_c$. Fig. 1.2 shows an example of dependence of the spin supercurrent between two virtual photons with respective precession frequencies ω_1 and ω_2 on the

hypothetical difference in the precession angles, $\Delta\varphi$, which, according to Eqs (1.16)-(1.17), is determined to be $\Delta\varphi = (\omega_1 - \omega_2)t$.

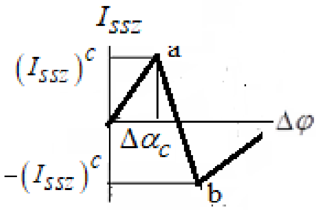

Figure 1.2. The dependence of the spin supercurrent I_{SSZ} between two virtual photons on the hypothetical difference in the precession angles $\Delta\varphi$. $(I_{SSZ})^C$ is the critical spin supercurrent. The line *a–b* corresponds to the phase slippage. $\Delta\alpha_C$ is the phase difference at which the phase slippage takes place.

Thus, Eq. (1.12) holds true in the absence of phase slippage, that is, under:

$$|\alpha_2 - \alpha_1| < \Delta\alpha_C . \qquad (1.19)$$

According to Eqs (1.16)–(1.17), the possibility of phase slippage is negligible if the difference $\Delta\omega = \omega_1 - \omega_2$ between the precession frequencies of the spins in the interacting virtual photons satisfies the following:

$$\Delta\omega \to 0 . \qquad (1.20)$$

6) The spin supercurrent is not an electric or magnetic process and, according to Maxwell’s model, propagates in a “finer” physical medium (the physical vacuum) than the molecular one. Therefore, the spin supercurrents cannot be screened by electromagnetic and, possibly, molecular screens.

7) The effectivity of action of spin supercurrent can decrease at an increase in the number of interacting virtual photons. Let us assume, for example, that one virtual photon with precession frequency $\boldsymbol{\omega}_{ex}$ interacts with a great number (w) of virtual photons. If the precession frequencies of the spins of all virtual photons are aligned with $\boldsymbol{\omega}_{ex}$, then the total spin supercurrent I_{sumz} is determined as a sum of the spin supercurrents between the virtual photon with precession frequency $\boldsymbol{\omega}_{ex}$, on the one hand, and the arbitrary *i*-th virtual photon (from *w* virtual photons), on the other. Using Eq. (1.12), we obtain:

$$I_{sumz} = -\sum_{i=1}^{w} \left(b_1 \Delta\alpha_i + b_2 \Delta\beta_i \right),$$

where $\Delta\alpha_i$ and $\Delta\beta_i$ are the differences in the precession angles and in the deflection angles between a virtual photon with frequency $\boldsymbol{\omega}_{ex}$, on the one hand, and the arbitrary i-th virtual photon (from w virtual photons), on the other hand.

If all the values and signs of $\Delta\alpha_i$ and $\Delta\beta_i$ are respectively equiprobable and $w \to \infty$, then

$$I_{sumz} \to 0. \qquad (1.21)$$

8) The degree of dependence of the value of spin supercurrent on the distance between interacting objects remains nonclear. Let us consider the following approaches to this problem.

All experimentally observed properties of quantum correlations are in accordance with the properties of spin supercurrent [9, 10]. At the same time, there was an experimental demonstration of quantum correlations over more than 10 kilometers [18]. The unique experiments were conducted in 2017 by Ji-Gang Ren et al. They conducted the first quantum teleportation of independent single-photon from a ground observatory to a low Earth orbit satellite - through an up-link channel (sputnik channel) at a distance of up to 1400 km [19]. In these experiments, a weak dependence of the effectivity of the action of the current between the virtual photons on the distance between them is observed.

9) The spin supercurrent belongs to pseudomagnetic interaction.

The pseudomagnetic interaction depends on the mutual orientation of the spins of interacting objects, virtual photons can be such objects. The character of a pseudomagnetic interaction is, in many aspects, analogous to that of magnetic interaction, which is why the interaction is called “pseudomagnetic”. However, the energy of this interaction is a thousand times greater than the energy of a magnetic interaction and the magnetic field does not influence it. This interaction includes not only a moment (spin supercurrent) acting on the spins of virtual photons and, consequently, on spins of virtual particles constituting the virtual photons, but a force $\mathbf{F}_{pm}$ acting on the virtual particles as well, which depends on their charges and mutual orientation of their spins [10,20,21].

$$\mathbf{F}_{pm} = k\left|\phi_{pm}(\mathbf{S}_1,\mathbf{S}_2)\right| q_1 q_2 / \left|q_1 q_2\right|, \qquad (1.22)$$

where $\phi_{pm}\left(\mathbf{S}_1,\mathbf{S}_2\right)$ is a function of the characteristics of the spins ($\mathbf{S}_1$ and $\mathbf{S}_2$) of interacting quantum objects; q_1 and q_2 are the electric charges of interacting quantum objects with due regard for their signs; factor k is determined as:

$$k = \begin{cases} 1, \; if \; \mathbf{S}_1 \rightarrow\rightarrow \mathbf{S}_2 \\ -1, \; if \; \mathbf{S}_1 \rightarrow\leftarrow \mathbf{S}_2 \end{cases}$$

If F_{pm}>0, the force is attractive, but if F_{pm}<0, the force is repulsive.