

# The physical aspect of the effects of metal nanoparticles on biological systems. Spin supercurrents

Liudmila B. Boldyreva

Correspondence: [boldyrev-m@yandex.ru](mailto:boldyrev-m@yandex.ru)



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Associate Professor, The State University of Management, Moscow, Russia.

## Abstract

As follows from the current studies, the therapeutic effect of nanoparticles on the cells of a biological organism is not determined in some cases by the electric or magnetic forces. The paper aims at showing that there is a physical process that might account for the features of the non-electromagnetic effects of nanoparticles on biological systems. An analysis is given of some features of the effects (non-electrostatic) of metal nanoparticles on biological systems, namely: the non-monotonic size-effect dependence, the dependence on nanoparticle form, the adhesion of certain metal nanoparticles to specific cells. It is shown that these features of the effects of nanoparticles on biological systems are analogous to the features of the interaction of spin structures in superfluid  $^3\text{He-B}$  by spin supercurrents. This approach allows one to improve the efficacy of therapeutic applications of nanoparticles, in particular, they make it possible to determine which metal would exert maximum effect on a definite biological system.

**Keywords:** Nanobiology, nanomedicine, metal nanoparticles, spin supercurrent, model of superfluid physical vacuum

## Introduction

The main applications of metal nanoparticles (NPs) in medicine are the targeted drug deliver, treatment, diagnosis, monitoring, and control of diseases. In this paper the following features of metal NPs effects on biological systems in the drug deliver and treatment of diseases are considered.

1. As follows from the current studies, the medical effect of metal compound NPs on the cells of a biological organism is not determined in many cases by the action of ions of the metals. For example, the toxic effect of AgNPs cannot be reduced to the action of  $\text{Ag}^+$  ions in equivalent concentrations; this conclusion was made in studies of AgNP interaction with bacteria [1,2] and fish embryos [3]. Therefore there are grounds to assume that the biological action of silver NPs can be effected through the mechanism different from that of  $\text{Ag}^+$  ions (that is, it is not due to electric forces).

2. There is a non-monotonic dependence of efficacy of action of NPs on a biological system (BS) on the size of NPs, that is, the non-monotonic "size-effect" dependence [1,4,5]. For example, in experiments with *E.coli* [5] the non-monotonic dependence of toxic effect of silver NPs on the particle size was established. **Figure 1** shows the type of dependence of normalized toxicity rate  $T/T'$  ( $T = T'$  at  $d = 9\text{nm}$ ) on the nanoparticle size  $d$ .

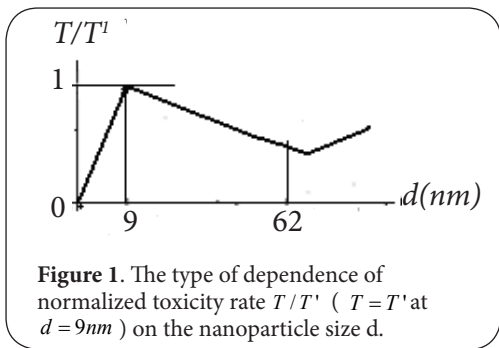
3. The efficacy of NPs depends on their form. For example, in the experiments on action of AgNPs on *E.coli* it was found [1,6] that the toxic action of AgNP depended on their form: triangular particles were more active than spherical ones.

4. Besides the active targeting using external physical factors (for example, a magnetic field or heating) there is a passive

targeting, in which case the drug deliver is performed due to the properties of medication itself and/or those of drug carrier [7,8]. Systems of passive targeting are known, which contain NPs of precious metals as drug carriers [1,9]. For example, gold composites may selectively target certain organs depending on the composite's size [10]; in particular, gold nanoshells help diagnose cancer cells [11]. In the case of passive targeting the active biological substances can penetrate deeply into the tissue, while the depth of penetration, for example, of the magnetic field in the active targeting does not exceed 15cm [7].

Note that the metals whose NPs "adhere" to certain organs would be present in the organism before the introduction of the NPs in it. For example, iron ions are known to be present in the form of reserve protein ferritin in spleen; silver is contained in brain, liver, kidneys and bones; gold is found in blood. The adhesion of colloid metal particles to the cell surface is experimentally established not to be due to electrostatic forces [12]. It is worthwhile noting that there are ways of amplifying the adhesion effect and increasing the number of cases where it can take place. For example, hyperthermia of tumor cells seems to induce modifications of the cell surface receptor molecules and thus tumor cells are recognized by the killer cells more readily [13].

5. The medical action of NPs is determined by their intrinsic properties and does not depend significantly on the presence of a protective shell. For example, here are the conclusions drawn by the researchers of the medical effect of AgNPs [1]: "Antimicrobial effect of AgNP is clearly expressed not only in water medium, but also in studies of solid materials with



**Figure 1.** The type of dependence of normalized toxicity rate  $T/T'$  ( $T=T'$  at  $d=9nm$ ) on the nanoparticle size  $d$ .

nanoparticles deprived of their protective shell.”

It is important to establish the mechanism of action of NPs, at least metal NPs, on biological systems. In spite of the extensive studies undertaken recently, it seems that many points here still remain unclear. Meanwhile, without distinct understanding of the processes underlying the biological effects of metal NPs one can hardly hope to give wellfounded recommendations for the safe application of metal NPs in medicine [1].

It is shown in this work that the above-mentioned features are like those of the interaction of spin structures in superfluid  $^3\text{He-B}$  through spin supercurrents. The author argues that the coincidence of the features of non-electrostatic effects of NPs on biological systems and the properties of the spin supercurrents emerging between the spin structures in superfluid  $^3\text{He-B}$  is not accidental and can be explained on the basis of modern physical concepts.

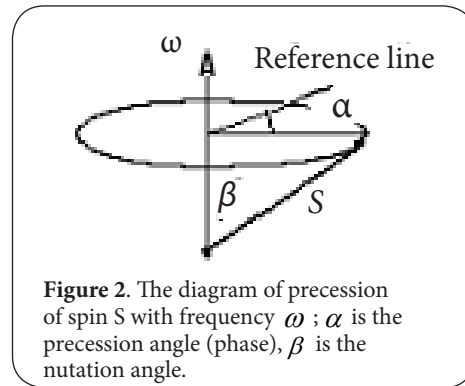
(1) According to quantum field theory, quantum entities create pairs of virtual particles, or particle-antiparticle pairs, in the physical vacuum. For the virtual particles the classical relation between mass, energy and momentum does not hold; however, they have spin which is the same as for the real particles and, consequently, spin correlations may take place. Thus all bodies as consisting of quantum entities may produce in the physical vacuum the spin structures consisting of virtual particles, and spin correlations can exist between such structures.

(2) The physical vacuum has the properties of superfluid  $^3\text{He-B}$ . The validity of endowing the physical vacuum with certain properties of superfluid  $^3\text{He-B}$  is substantiated in a number of works. For example, in [14-16] analogies are drawn between some properties of superfluid  $^3\text{He-B}$  and gravitational properties of space. It has been shown that endowing the physical vacuum with the properties of superfluid  $^3\text{He-B}$  makes it possible to explain some optical effects [17,18], the wave properties of matter, superconductivity, the effects of ultra-low doses of biologically active substances and effects of cavity structures on biological systems [18-20].

### Some properties of spin supercurrents in superfluid $^3\text{He-B}$

*Definition of spin supercurrents.* In superfluid  $^3\text{He-B}$  there may

exist spin structures where coherent precession of spins of  $^3\text{He}$  atoms takes place. Such a structure is called a homogeneously precessing domain (HPD) [21-24]. An HPD is characterized by spin  $S$ , precession angle (phase)  $\alpha$ , nutation angle  $\beta$ , and precession frequency  $\omega$  (Figure 2).



**Figure 2.** The diagram of precession of spin  $S$  with frequency  $\omega$ ;  $\alpha$  is the precession angle (phase),  $\beta$  is the nutation angle.

The precession and nutation angles determine the spin part of the order parameters for superfluid  $^3\text{He-B}$ , and there are processes that tend to make equal the respective angles throughout the whole volume of the superfluid. Such processes in superfluid  $^3\text{He-B}$  are spin supercurrents. In the case where the precession frequencies are aligned with axis  $z$ , the spin supercurrent component in the direction of axis  $z$ ,  $J_z$ , is determined as:

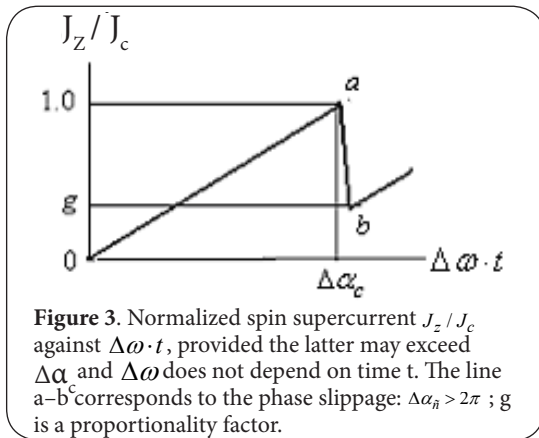
$$J_z = -b_1 \frac{\partial \alpha}{\partial z} - b_2 \frac{\partial \beta}{\partial z}, \quad (1)$$

where  $b_1$  and  $b_2$  are proportionality factors depending on  $\beta$  and the properties of the medium. In a HPD its energy  $U$  is related to the frequency  $\omega$  of precession as:

$$U = S\omega. \quad (2)$$

*The phase slippage.* In superfluid  $^3\text{He-B}$  such a phenomenon as phase slippage exists. At a definite difference in precession angles,  $\Delta\alpha_c$ , determined by the properties of the superfluid medium, a precession phase slippage (drop) by the value of  $2\pi n$  ( $n=1,2,\dots$ ) takes place. The critical spin supercurrent  $J_c$  corresponds to the value  $\Delta\alpha_c$ . Figure 3 shows an example of the normalized spin supercurrent  $J_z/J_c$  between two spin structures as a function of  $\Delta\omega \cdot t$ , where  $\Delta\omega$  is the difference between the precession frequencies in the structures,  $t$  is time. In the example  $\Delta\omega \cdot t$  is greater than  $\Delta\alpha_c$  and  $\Delta\omega$  does not depend on  $t$ . The line  $a-b$  corresponds to the change in the supercurrent in the process of phase slippage and the phase slippage occurs at  $\Delta\alpha_c > 2\pi$ . In the course of phase slippage the spin supercurrent value changes from  $J_c$  to  $gJ_c$ ; proportionality factor  $g$  is a function of  $b_1$  and the phase slippage value.

*Dependence of spin supercurrent on the configuration of spin structures.* The spin supercurrents between HPDs depend on the mutual position of the latter in space. Let us consider



**Figure 3.** Normalized spin supercurrent  $J_z / J_c$  against  $\Delta\omega \cdot t$ , provided the latter may exceed  $\Delta\alpha$  and  $\Delta\omega$  does not depend on time  $t$ . The line a–b corresponds to the phase slippage:  $\Delta\alpha_n > 2\pi$ ;  $g$  is a proportionality factor.

two versions of configuration of a sequence of HPDs ( $HPD_1, \dots, HPD_p, \dots, HPD_q, \dots, HPD_r$ ) having respective precession frequencies  $\omega_1, \dots, \omega_p, \dots, \omega_q, \dots, \omega_r$ . In the first version all precession frequencies are aligned with axis **Z** (**Figure 4a**) and due to action of spin supercurrents the respective characteristics of the above HPDs may be made equal. If so, under the equation (1) the spin supercurrent ( $J_{p-q}$ ) between arbitrary  $HPD_p$  and  $HPD_q$  may become zero, i.e.

$$(J_{p-q})_a = 0. \quad (3)$$

In the second version the sequence of HPDs makes up a ring, thus the straight line coincident with the axis **Z** will become a circumference, see **Figure 4b**. If the precession frequencies of the HPDs in question,  $\omega_1, \dots, \omega_p, \dots, \omega_q, \dots, \omega_r$  are tangential to the circumference, that is, the precession frequencies are not aligned, then the equalization of the respective angles of precession and nutation angles of any two HPDs cannot take place, and, according to equation (1), the spin supercurrent between any two HPDs will never be zero. Thus for the spin supercurrent ( $J_{p-q}$ )<sub>b</sub> between arbitrary  $HPD_p$  and  $HPD_q$  the following holds:

$$(J_{p-q})_b \neq 0. \quad (4)$$

So the space between the HPDs that form a ring will be “filled” with spin supercurrents. (The non-zero spin supercurrents will be present even if a curved chain of HPDs is open, that is, does not make a ring.) Thus the configuration of the spin structures between which spin supercurrents arise will affect the magnitude of the supercurrents.

*The efficacy of spin supercurrent.* Generally, determination of time dependency of the magnitude of the spin supercurrent between two HPD is a difficult problem, because the speed of transmission of information of the existence of order parameter gradient is, in theory, infinite, and the speed of the spin supercurrent is finite. Besides, a possibility of phase slippage should be taken into account.

The respective precession and nutation angles of the interacting HPDs will become equal, provided the distance

$X$  between them and the difference between their precession frequencies,  $\Delta\omega$ , satisfy the following conditions:  
 $X \rightarrow 0$  and

$$\Delta\omega \rightarrow 0. \quad (5)$$

An increase in the number of interacting HPDs may result in a decrease of efficacy of the interaction caused by spin supercurrents. Let us consider the case where one HPD ( $HPD_0$ ) interacts with several HPDs ( $HPD_1, \dots, HPD_w$ ). If the precession frequencies of all HPDs are aligned, then according to (1) the total spin supercurrent  $J_{sum}$  between  $HPD_0$  and  $HPD_1, \dots, HPD_w$  may be defined as

$$J_{sum} = \sum_{i=1}^w j_i, \quad (6)$$

where  $j_i$  is spin supercurrent between  $HPD_0$  and  $HPD_i$ , under (1), is determined as:

$$j_i = b_1 \Delta\alpha_i + b_2 \Delta\beta_i, \quad (7)$$

where  $\Delta\alpha_i$  and  $\Delta\beta_i$  are the respective differences in precession and nutation angles between the  $HPD_0$  and  $HPD_i$ . Using Eq. (7) in (6), we obtain:  $J_{sum} = \sum_{i=1}^w (b_1 \Delta\alpha_i + b_2 \Delta\beta_i)$ .

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

$$J_{sum} \rightarrow 0. \quad (8)$$

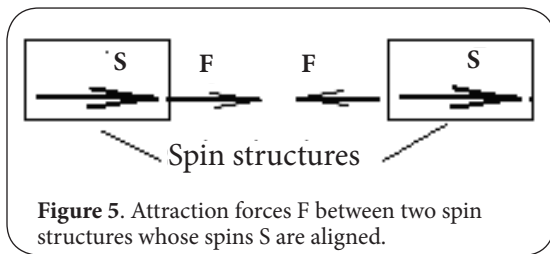
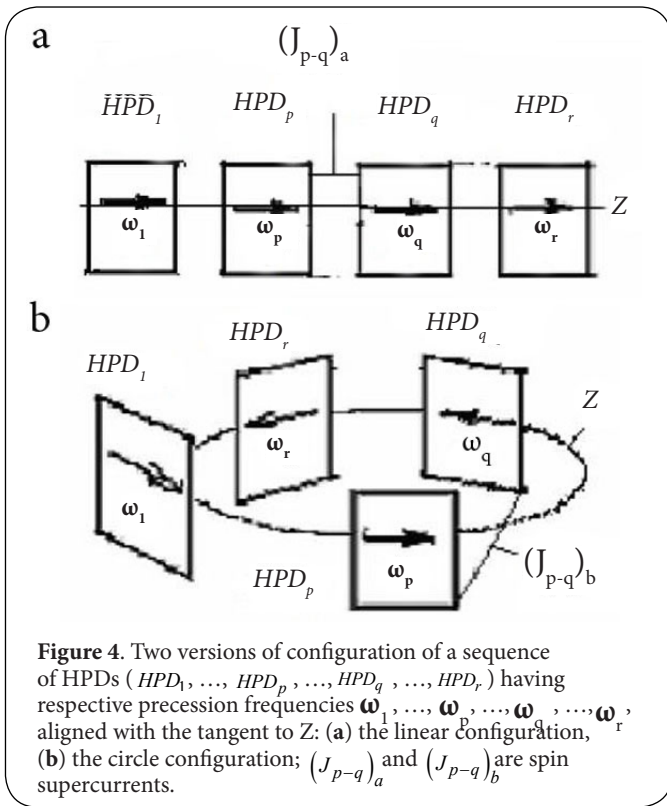
*The force interaction between spin structures.* In superfluid  $^3\text{He-B}$  the motion of  $^3\text{He}$  atoms constituting a Cooper pair relative to each other corresponds to the  $p$ -wave state. In this state, attractive forces act between like-charged particles with the spins oriented in the same direction. Under the definition expressed by equation (1), the spin supercurrent emerging between two spin structures “tends” to make equal the respective characteristics of the structures. If such equalization takes place, the following equalities hold:

$$\Delta\alpha = 0, \quad \Delta\beta = 0, \quad \Delta\omega = 0, \quad (9)$$

where  $\Delta\alpha$ ,  $\Delta\beta$ ,  $\Delta\omega$  are the difference between the respective precession angles, nutation angles, and precession frequencies of the interacting spin structures. Under these equalities, the spins of spin structures will be aligned and attraction forces **F** may arise between the spin structures (**Figure 5**).

### Matching of the features of effects of metal nanoparticles on biological systems and the properties of spin supercurrents in superfluid $^3\text{He-B}$

According to quantum field theory, quantum entities (that is, the entities whose state is described by a wave function: electrons, neutrons, protons, etc.) create pairs of virtual particles in the physical vacuum. The virtual particles have spin which is the same as for the real particles. Hence it follows that (1) spin correlations can take place; (2) the virtual particle spin has no definite direction, and by the magnitude of spin the magnitude of its projection onto a preferential direction is



meant; this can be interpreted as a precession of the spin about the preferential direction and allows one to introduce the frequency of the precession, the angle of precession, angle of nutation and energy,  $U_S$ , which is determined by precession frequency  $\omega_S$  and spin  $S_S$  as

$$U_S = S_S \omega_S. \quad (10)$$

Consequently, nanoparticles and biological systems as consisting of quantum entities may produce spin structures in the physical vacuum, and spin correlations may take place between them.

*The spin correlations are responsible for the first feature of the effects of metal nanoparticles on biological systems (see Introduction): the possibility of action of nanoparticles on biological systems by non-electric forces.*

In this section it will be shown that under the assumption that the properties of the spin correlations are analogous to those of spin supercurrents in superfluid  $^3\text{He-B}$ , the features of

effects of NPs on BS mentioned in Introduction can be explained on the basis of the properties of spin supercurrents between spin structures in superfluid  $^3\text{He-B}$ .

–In superfluid  $^3\text{He-B}$  the dependence of the spin supercurrent between the interacting spin structures on the gradients of their precession angles is not monotonic because of the phase slippage effect. As concerns NPs, this means that the dependence of the efficacy of action of NPs upon a BS on the NP’s size (specified, for example, in terms of the number of quantum entities) may be non-monotonic.

*Thus the second feature of the effects of metal nanoparticles on BS (see Introduction), i.e. the non-monotonic “size-effect” dependence is a result of the phase slippage effect taking place in the spin structures produced by the nanoparticles and BS in the physical vacuum.*

–According to the properties of superfluid  $^3\text{He-B}$ , the value of spin supercurrent, see equations (3) and (4), depends on the configuration of the spin structures between which it emerges. *Thus the third feature of the effects of metal nanoparticles on BS (see Introduction), namely, the dependence of efficacy of nanoparticles’ action on the form of the nanoparticles is due to the dependence of spin supercurrent on the configuration of the spin structures between which the spin supercurrent emerges.*

–According to (1), spin supercurrents emerge between spin structures having different values of their respective characteristics. If the action of spin supercurrent between spin structures produced in the physical vacuum by the NPs and BS results in equalization of respective characteristics of the spin structures, then the differences between respective nutation angles,  $\Delta\beta$ , precession angles,  $\Delta\alpha$  and precession frequencies,  $\Delta\omega$ , of the spin structures will satisfy equations (9). In this case attraction forces can exist between the spin structures and, consequently, between the NPs and BS that produced the structures.

Equalities (9) hold most strictly for those NPs that are contained already in the BS and, consequently, determine the range of spin precession frequencies for the spin structure produced by BS. In this case the precession frequencies of the spin structures produced by the NPs and BS satisfy the condition (5) and the spin supercurrent between the structures causes the maximum equalization of their respective characteristics. Condition (5) can be satisfied by means of forced changing of the precession frequencies of the spin structures produced by BS (for example, this may be done by heating the BS [7,8]).

*Thus the fourth feature of the effects of metal nanoparticles on BS (see Introduction), i.e. the possibility of adhesion of nanoparticles of certain metals to specific cells of the biological system, in particular to those which contain already the same metal, is due to the fact that between the spin structures with the respective equal precession frequencies, nutation angles and precession angles there exist attraction forces.*

*Note.* Attractive forces between spin structures may arise if the precession frequencies are oriented in the same direction

(in the equalities (9)  $\Delta\omega$  is a vector). This condition imposes certain requirements on the configuration of interacting spin structures and, respectively, the configuration of the bodies producing the spin structures. So we may suppose that 3D nanoparticles would adhere to 3D cells of the BS, because such NPs and biological system cells may produce spin structures with similar orientation of spins in the physical vacuum. This may account for the experimental fact that 3D nanoparticles can penetrate to a DNA molecule, having a spiral shape, deform and even unwind the spiral. Examples of such NPs are fullerenes (computer simulation has shown that fullerenes, namely, spherical C60 molecules, are potentially dangerous to DNA molecules [25]) and dendrimers (dendrimers of the 3D and higher generations have the form close to a sphere) [26].

–Quantum entities produce spin structures in the physical vacuum, not in a molecular medium. Therefore, spin supercurrents emerging between the structures propagate in a “finer” physical medium (namely, the physical vacuum) than the molecular one and may not be shielded by molecular substances.

*This property of spin supercurrents may underlie the fifth feature of the effects of metal nanoparticles on BS (see Introduction): the independence of the action of nanoparticles on biological systems on the existence of nanoparticle’s protective shell.*

## Discussion

I. According to Eq. 1, the value of spin supercurrent between a NP and BS is determined only by the characteristics of the spin structures produced by the NP and BS in the physical vacuum. Consequently, any other quantum entity which produces in the physical vacuum the spin structure with the same respective characteristics as those of the spin structure produced by the NP will exert the same effect on the BS as the NP in question. Below this is explained in detail using the photon as an example.

The pair of virtual particles produced by a photon in the physical vacuum is converted into real particles (a pair of electron and positron or a pair of proton and antiproton), if the energy of the photon equals the total energy of the pair of real particles produced [27]. This means that the energy of a pair of virtual particles, that is, the energy of the spin structure produced by the photon in the physical vacuum  $(U_S)_{ph}$  is equal to the energy of photon,  $U_{ph}$ :

$$(U_S)_{ph} = U_{ph}. \quad (11)$$

For the total spin of the pair of virtual particles produced by the photon,  $(S_S)_{nh}$ , we have:

$$(S_S)_{ph} = \hbar. \quad (12)$$

Taking Eq. (10) into account and comparing the well-known relation between energy  $U_{ph}$  and photon frequency  $\omega_{ph}$ ,  $U_{ph} = \hbar\omega_{ph}$ , with Eqs. (11)–(12), we obtain that the precession

frequency in the spin structure produced by a photon in the physical vacuum  $(\omega_S)_{ph}$  is equal to the photon frequency:

$$(\omega_S)_{ph} = \omega_{ph}. \quad (13)$$

Thus according to (13), the effect on a biological system by a NP whose spin structure has precession frequency  $\omega$  is analogous to the effect on the BS by a photon with frequency  $\omega$ .

It agrees with Paracelsus’ views on treatment of diseases [28]. The outstanding medieval physician and philosopher thought that light emitted by celestial bodies can cure certain diseases: for example, the disease whose symptoms are like those of anaemia should be cured by radiation of Mars. Note that in the modern medicine anaemia is treated by iron-containing preparations; and Mars is characterized by the presence of iron oxide on its surface, which accounts for the color of the planet: “red planet”.

II. According to (5), the effect of NP on BS is most pronounced, if the precession frequencies in the spin structures produced by NP and BS in the physical vacuum are the same. Evidently, the condition (5) holds most accurately in the case where the substance that constitutes the NP has been contained in the BS before the action of the NP on the latter. This means that for a metal to affect a BS it is necessary that the same metal has been already contained in the BS. This is characteristic as well of the homeopathic medicine and is referred to as “kinetic paradox”: the effect of a homeopathic remedy on a BS is the strongest when the latter contains the same substance which is present in the remedy [19].

*Note.* It is possible for NPs to affect a BS indirectly, through an intermediary which has acquired the properties of the NPs as a result of the preceding interaction with the latter. That is, if there is an object or medium (for example, water) and the precession frequency of its spin structure becomes equal to that of the spin structure of the NPs as a result of interaction between the spin structures, then the object or medium acquires a capacity to produce the same effect on the BS as the NPs.

III. While choosing the type of NPs whose effect on a BS is the strongest, it is essential to observe condition (5): the equality of the precession frequencies in the spin structures produced by the NP and BS in the physical vacuum. Below the physical aspect of the condition is discussed in more detail. Let us assume that the equation similar to (11) is valid for the energy  $U_q$  of any quantum entity, i. e.

$$(U_S)_q = U_q, \quad (14)$$

$(U_S)_q$  is the energy of the spin structure produced by the quantum entity in the physical vacuum. According to quantum theory, electric interactions of electrically charged real particles are effected by virtual photons. This means that at least for spin  $(S_S)_q$  of the spin structure (virtual photon)

produced by the electrically charged particle in the physical vacuum the following holds:

$$(S_S)_q = \hbar. \quad (15)$$

Taking Eq. (10) into account and comparing the well-known relation between energy of quantum entity and frequency of its Schroedinger wave function,  $\omega_{Sh}$ , i.e.,  $U_q = \hbar\omega_{Sh}$ , with Eqs. (14)-(15), we obtain that the precession frequency in the spin structure produced by a quantum entity in the physical vacuum  $(\omega_S)_q$  is equal to the frequency of quantum entity's Schroedinger wave function:

$$(\omega_S)_q = \omega_{Sh}. \quad (16)$$

Thus taking into account Eq (16), one can draw the following conclusion: for the action of nanoparticles on a biological system to be effective it is necessary that the frequency of the Schroedinger wave function of quantum entities constituting the nanoparticles were of the same order of magnitude as the frequency of the Schroedinger wave function of quantum entities constituting the biological system. According to the definition of the frequency of the Schroedinger wave function, the equality of the frequencies of the Schroedinger wave functions for quantum entities means that their energies are equal.

IV. In the present physical model of action of metal NPs on biological systems the fact that NPs are of small size is of fundamental importance. According to (6)-(8), with a large size of NPs the spin supercurrent ceases to be the factor that governs the effects of NPs on biological systems. (The change in the spin supercurrent due to the slippage effect does not affect this conclusion).

*Note.* The determining of the NP's size (in terms of the number of quantum entities; in Eqs. (6)-(8) this number is denoted as  $w$ ) at which the spin supercurrent ceases to be the factor that governs the effects of the NPs on the biological system is an involved problem in the general case, because it is necessary to know the magnitude of the spin supercurrent and the characteristics of spin structures produced by the NPs and the biological system in the physical vacuum. Let us consider the specific case: the toxic effect of silver 9nm NPs on a biological system in experiments with *E.coli*, see **Figure 1**. Taking that NPs are spheres and that the silver atom diameter is about 0.144nm, with the atom itself containing 155 quantum entities (protons, neutrons and electrons), we obtain that a silver 9nm nanoparticle contains approximately  $38 \cdot 10^6$  quantum entities. (We assume for simplicity sake that the spin structures produced in the physical vacuum by protons, neutrons and electrons of the silver atom have the same characteristics.) Since with this number of quantum entities the effect of silver NPs on the biological system, caused by spin supercurrents, is highly pronounced, the value of  $w$  must be greater than  $38 \cdot 10^6$ .

## Conclusion

It has been shown that some features of non-electric and non-magnetic effects of metal nanoparticles on biological systems are analogous to those of spin supercurrents between spin structures in superfluid  $^3\text{He-B}$ .

The results obtained in this work can be used as a basis for improving therapeutic applications of nanoparticles, in particular, they make it possible to determine which metal would exert maximum effect on a definite biological system.

## List of abbreviations

NP: NanoParticle

BS: Biological System

HPD: Homogeneously Precessing Domain

## Competing interests

The author declares that she has no competing interests.

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