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Hypothesis of macroscopic quantum state in biological systems and discussion on the possibility of its experimental verification

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ABSTRACT

Earlier it was noted that the functioning of biological systems is accompanied by a very low level of energy dissipation, and it was assumed that a physical mechanism similar to that which works in superconductivity can operate here. The paper proposes a hypothesis that the phenomenon of life is not based on superconductivity, but on some so far unexplored macroscopic quantum state of organic structures making up the cell. It is assumed that this state is also characterized by the presence of an energy gap in the electronic spectrum, which makes the state stable and provides a low level of energy dissipation. The possibility of using optical spectroscopy methods for identifying the energy gap in biological objects is analyzed. It is assumed that the virus is alive inside the host cell, but not alive outside the host cell. It is proposed to use Raman spectroscopy of the process of bacterial infection with phages to search for the energy gap. This should confirm or refute the main hypothesis, as well as provide an opportunity to answer the question: "Are viruses alive?"

The functioning of biological systems is accompanied by a very low level of energy dissipation (Igamberdiev, 1993). In (London, 1950), an assumption was made that a certain quantum mechanism inherent in the system as a whole operates in biological processes, similar to superconductivity and superfluidity in condensed matter physics. This provides the system with a characteristic stability of quantum states with the possibility of changes without the participation of dissipation processes. In (Little, 1964), a possible mechanism for room temperature superconductivity was proposed, which could take place in a hypothetical organic polymer with a structure similar to DNA.

The issues of local superconductivity in molecules were considered as follows (Kresin and Ovchinnikov, 2020). Complex so-called conjugated molecules contain both electrons in internal orbits (σ-electrons) and external electrons (π-electrons). In this case, π-electrons are able to move along the entire molecular σ-skeleton (the nucleus of atoms of a molecule with σ-electrons), i.e. are collective or delocalized. In other words, π-electrons are like free electrons in a conductor. In (Kresin, 1971), the possibility of pair correlation in a π-electron system was shown, similar to the formation of Cooper pairs in a superconductor. In this case, the connection between electrons in pairs is due to their interaction with the σ-core, which plays here a role similar to that of the lattice in superconductors. Complex molecules with conjugated bonds are part of biologically active substances. In (Kresin, 1971, 1978) there is a reference to the book (Pullman and Pullman, 1963), which ends with the conclusion that the presence of an electron cloud in conjugated molecules can be considered as the main basis of life. In (Kresin, 1971), it is assumed that the pair correlation of collective electrons in biologically active substances provides stability similar to that observed in superconducting metals.

Let us clarify that the superconducting state in complex molecules does not mean that there an electric current can flow with zero resistance. This is just one of the characteristic (but not in this case) properties of the superconducting state, along with a number of others. One of them is the presence of an energy gap in the density of electronic states near the Fermi level, within which there are no allowed electron energy levels (Fig. 1). The electrons entering the Cooper pair have opposite spins, therefore the Cooper pair of electrons has a total spin equal to zero and behaves like a boson, i.e. does not obey the Pauli exclusion principle. Bose condensation of Cooper pairs occurs at the Fermi level, located in the middle of the energy gap. When a Cooper pair breaks up, the electrons entering it can only occupy levels above the energy gap (the states below the gap are already occupied). This leads to an increase in the energy of the system, but the system tends to occupy a state with a minimum energy level. Thus, the presence of an energy gap increases the stability of the superconducting state. The gap width 2Δ corresponds to the binding energy of the Cooper pair of electrons. The BCS theory predicts the following gap width for conventional superconductors at $T = 0$ K: $2\Delta = 3.52 k_B T_c$, where T_c is the superconducting

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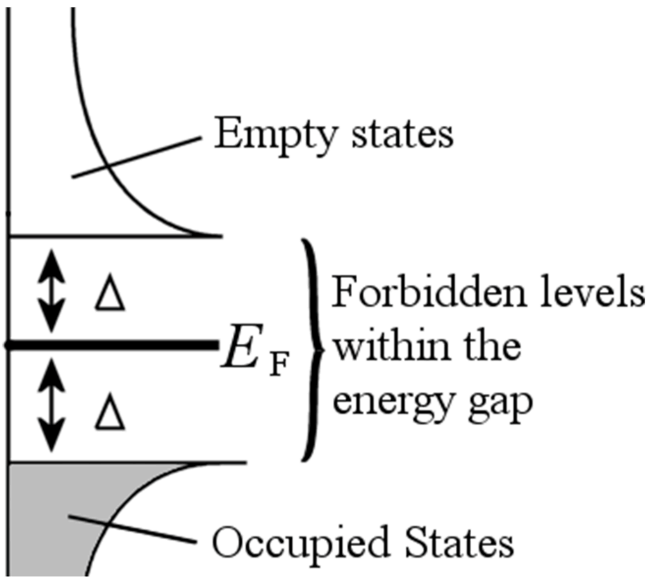

Fig. 1. Electron energy-level diagram of superconductor. E_F is the Fermi level; the Cooper pairs of electrons are located there; 2Δ is the gap width.

transition temperature and k_B is the Boltzmann constant (Schmidt, 2013). The energy gap for high-temperature superconductors (Timusk and Statt, 1999) and for the charge density wave (Monceau, 2012) differ from the above expression, but also have the order of $2k_BT_a$, where T_a is the temperature of the superconducting or Peierls transition, respectively.

Our hypothesis is that the phenomenon of life is based not on superconductivity, but on a certain "not yet investigated" macroscopic quantum state of organic structures that make up the cell (Smolovich, 2019, 2021). We will denote this state by the letter V (vita) (Ivanitskii, 2010); in fact, this state is life. The words "not yet investigated" are put in quotation marks, since biology has been doing this research for many years. However, let's try to think about what can be said about state V. First, the organic structures that make up a cell are much more complex than objects that are usually studied in condensed matter physics, which suggests that state V is much more complicated than, for example, superconductivity. Second, it is logical to assume that the stability of the V state is also provided by the presence of an energy gap in the electronic spectrum. We assume that the width of this energy gap is also of the order of $2k_BT_V$, where T_V is some temperature typical for living organisms, for example, 300 K. This gives an estimate of the band gap of about $5\cdot10^{-2}$ eV. We do not know what else can be said about state V. It seems to us that studies of state V should begin with an experimental verification of the presence of an energy gap in the electronic spectrum.

There are various experimental methods for determining the superconducting energy gap. Among them, optical spectroscopy methods seem to be the most suitable for studying living objects, since these methods are non-contact. The use of these methods to determine the energy gap in conventional and high-temperature superconductors can be found in (Timusk, 2011; Misochko, 1998, and references therein). Most studies of biological objects were carried out in the spectral range between 600 cm^{-1} and 2000 cm^{-1}. When studying bacteria and phages, the following types of optical spectroscopy were used: Raman spectroscopy and surface-enhanced Raman spectroscopy (Goeller and Riley, 2007; Hamasha et al., 2013; Vishnupriya et al., 2013; Li et al., 2019; Pilat et al., 2020; Dhankhar et al., 2021; Nagpal et al., 2021), coherent anti-Stokes Raman spectroscopy (Downes et al., 2010), infrared Fourier spectroscopy (Vargas et al., 2009), time-resolved infrared spectroscopy (Chen et al., 2014; de La Harpe et al., 2018), fluorescence spectroscopy (Nagpal et al., 2021). In (Pilat et al., 2020), a spectroscopic study of a single bacterium was carried out. In this study, the bacterium was fixed in the field of view of a confocal microscope using Raman optical tweezers. In our opinion, Raman spectroscopy should be considered the preferred method for detecting the energy gap in living structures.

However, the spectra of even simple biological objects, such as prokaryotes or viruses are quite complex, which makes it difficult to identify the assumed energy gap. Comparison of the spectra of protozoa in a living (V, vita) and inactivated (M, mort) state (Ivanitskii, 2010) can help identify the energy gap. This will be analogous to comparing the spectra of a superconductor at temperatures below and above the superconducting transition point. Let us demonstrate this with the example of Fig. 2 taken from (Misochko, 1998), which displays Raman spectra of $Bi_2Sr_2CaCu_2O_{8+x}$ crystals in the normal and superconducting states under excitation with a 633-nm laser line. $Bi_2Sr_2CaCu_2O_{8+x}$ is a high-temperature superconductor with a superconducting transition temperature Tc = 89 K. When a crystal becomes superconducting, the electronic Raman spectrum undergoes intensity redistribution, which reflects the specific features of the superconducting state. The depression of scattering at low frequencies with decreasing temperature is connected with the opening of the superconducting gap, whereas the peak, which is not observed in the normal state, is assigned to the new scattering channel associated with Cooper-pair breaking.

We propose to use viral spectroscopy to find the energy gap. Opinions differ as to whether viruses are a life form or organic structures that interact with living organisms. Until now, this dispute seemed insoluble due to the lack of a criterion for the belonging of some object to living or nonliving systems. According to our hypothesis, such a criterion may be the presence of an energy gap in the electronic spectrum of the object. When viruses are outside the host cell, they do not exhibit vital characteristics in the form of metabolism, replication, etc. But penetrating into the host cell, the virus is actively involved in biological processes. We assume that the virus is alive inside the host cell, but not alive outside the host cell. If our assumption is correct, then the virus is a

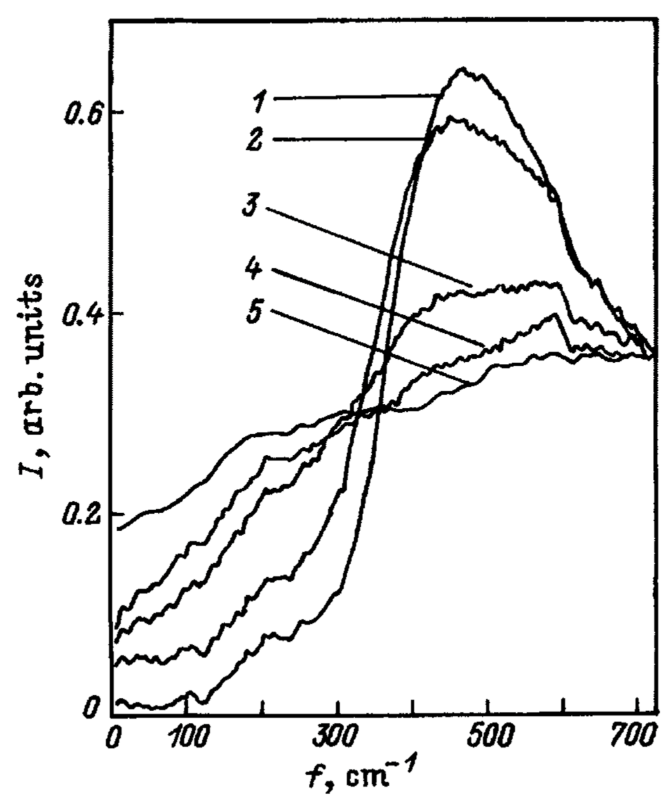

Fig. 2. (Taken from Misochko, 1998). Raman scattering spectra of $Bi_2Sr_2CaCu_2O_{8+x}$ crystals obtained under excitation in the basal *ab* plane with a He–Ne laser at different temperatures, both above and below the superconducting point T_c = 89 K. T(K): 1–5, 2–55, 3–75, 4–90, 5–295.

unique organism capable of passing from an nonliving state to a living one and back. The process of virus "revival" after it enters the host cell is of particular interest. In principle, this process can be investigated using time-resolved infrared spectroscopy (Chen et al., 2014; de La Harpe et al., 2018). Note that in (Ivanitskii, 2010) viruses are called "organisms at the edge of life". In (Koonin, 2011; Koonin et al., 2017) viruses are considered to play an important role in the evolution process. Thus, we propose the use of viruses inside and outside the host cell as markers of V and M states. The process of infecting bacteria with phages is suitable for these studies. In this case, it is necessary to compare the spectra of phage DNA before entering the bacterial cell and while the phage DNA is inside the cell. It should be taken into account that during infection, only the phage DNA gets inside the bacterium, and its protein coat (capsid) remains outside the membrane. In addition, when the phage DNA enters the cell, the bacterial activity is altered due to the infection. In some processes, phage DNA is directly involved, which leads to a change in its spectrum and makes it difficult to identify the energy gap. A special task is to separate the spectra of phages, bacteria and the solution in which they are located. For this, there are special methods (Ong et al., 2012), which are successfully used, including in the spectroscopy of phages and bacteria. In particular, these methods make it possible to distinguish between the spectra of bacteria and phages, as well as the spectra of different phages (Goeller and Riley, 2007). If the experiment reveals the presence of an energy gap in the virus inside the host cell and its absence in the virus outside the host cell, then our assumption that the virus enters a live state only inside the host cell will be confirmed.

The physical nature of the phenomenon of life is still unknown. It seems strange to us that this issue is rarely discussed in the scientific literature. The question of the origin of life is discussed more often. The answer to the last question is complicated by the fact that life on Earth originated about 4 billion years ago. As wittily noted in (Szostak, 2016): "After all, we can't go back in time to the early Earth and watch the process unfold, so we may never know for sure precisely how life evolved here on Earth." Also, how to answer this question without understanding what life is? The last issue was discussed, in particular, in (Ivanitskiy, 2010). There it comes down to the problem of defining the concept of life, which, by the presence or absence of some feature or set of features, can distinguish between living and inanimate matter, which turns out to be a very difficult task. This approach seems to be more of a philosophical nature. In our opinion, understanding the physical mechanism underlying the phenomenon of life is much more important than defining what life is. This article discusses the hypothesis that life can be viewed as a macroscopic quantum state of organic structures that make up a cell, which is characterized by the presence of an energy gap in the electronic spectrum. It is proposed to use Raman spectroscopy of the process of bacterial infection with phages to search for the energy gap. This should confirm or refute the hypothesis, as well as make it possible to answer one of the "insoluble" questions: "Are viruses alive?"

Declaration of competing interest

None.

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