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Fröhlich H. Long-range coherence and energy storage in biological systems.
Int. J. Quantum Chem. 2:641-9, 1968.
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Biological systems are expected to have a branch of longitudinal electric modes in a frequency region between 10^{11} and 10^{12} sec⁻¹. They are based on the dipolar properties of cell membranes, of certain bonds recurring in giant molecules (such as H bonds), and possibly on pockets of nonlocalized electrons. It is shown that if energy is supplied above a certain mean rate to such a branch, then a steady state will be reached in which a single mode of this branch is very strongly excited. The supplied energy is stored in a highly ordered fashion expressed in long-range phase correlations. [The *SCI*® indicates that this paper has been cited in over 160 publications.]

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The history of this paper goes back to about 1938 when my late friend Max Reiss informed me of the very small electric potential difference of 100 mV that has been found to be maintained by biological membranes. Their thickness on the order of 10^{-6} cm I found yielded the extraordinarily high electric field of 10^5 V/cm. Through my work on dielectric breakdown I was aware that ordinary materials will sustain such fields only if special precautions are taken. Also, one can then expect dipolar vibrations in the frequency range of 10^{11} - 10^{12} Hz corresponding to mm electromagnetic waves, which were not available at the time.

I considered it characteristic for biology to work in these difficult regions but hoped that experimental verification was possible. In fact, Willis Jackson expected to be able to produce mm waves. It was then imperative to find a biologist interested in physics, and, in fact, Victor Rothschild was greatly interested in

these possibilities. I remember that he proposed to investigate blood.

We had already had several preliminary meetings when this research was abandoned due to the outbreak of war. I had not forgotten these ideas when, in about 1966, I was asked by M. Marois of the Institut de la Vie, Paris, to give an introductory talk at a planned meeting on "Theoretical Physics and Biology." Through my involvement with superconductivity I had learned that a single idea (electron-phonon interaction) must be supplemented by a second one (coherence) to produce a theory. Long-range phase correlations, i.e., coherence, had been found to be a general concept required in the description of a nontrivial (non-spatial) order as it exists in superconductors, lasers, and superfluids. Relevant in these cases is the existence of a nonlinear interaction.

The order in biological systems might also be of this nature, and I thus considered the system of electric polarisation waves as might be based on membranes and other regions, assumed that they are excited by the supply of energy as might arise from metabolism, and supposed that they could emit this energy through interaction with a heat bath so that a steady state is reached. With the introduction of a simple nonlinear interaction, and when the rate of energy supply exceeds a critical value, a steady state will be reached in which a single mode of oscillation is very strongly, i.e., coherently, excited. This phenomenon was found to have considerable similarity to the low-temperature condensation of an Einstein-Bose gas.

It was likely, of course, that this possibility might have far-reaching biological consequences. In fact, a few years later publications in the Soviet Academy of Sciences presented a great number of remarkable effects on the influence of weak coherent mm waves on a variety of biological properties.^{1,2} Clearly mm wave spectroscopy had by then been developed in Russia.

A very great number of theoretical and experimental investigations followed and are still pursued at present.^{3,4} They do, however, all make use of the general concept of coherent excitations of electric vibrations, originally introduced in my 1968 paper.

1. Livshits M A. O vozmozhnosti Boze kondensatsii v biologicheskikh sistemakh (Possible Bose condensation in biological systems). *Biofizika SSSR* 22:744-6, 1977.
2. Moskalenko S A, Pokatilov E P, Migel M F & Kiselyova E S. Bose condensation of phonons in biological systems. *Int. J. Quantum Chem.* 16:745-52, 1979.
3. Hasted J B. The biomolecular effects of electromagnetic radiation. Classical or quantum physics? *J. Bioelectricity* 4:367-87, 1985.
4. Mascarenhas S. Bioelectrets: electrets in biomaterials and biopolymers. *Top. Appl. Phys.* 33:321-46, 1987.