**Interview on ‘Quantum Biology’**

**Questions: Frank Grotelüschen**
**Answers: Prof. Dr. Michael Thorwart (Universität Hamburg)**

1. What, in simple words, actually distinguishes quantum physics from classical „everyday” physics? For which systems or under which circumstances does it have to be applied?

Quantum physics is one major pillar of physics and includes classical physics as a limit range. It comes into effect when matter in the size range of atoms, molecules and below is described. Also, the complete description of the interaction of light and matter in the energy range of the excitations of atoms and molecules requires quantum physics. For physical systems with many particles at low temperatures (i.e., at a higher ordering of the particles), quantum statistics is required. Consider, for example, superconductivity or the Bose-Einstein condensation of ultracold atom gases. These are major quantum many-body phenomena. Quantum physics describes properties and dynamical processes with notions, which are entirely different from those of classical physics. They often even do not have an intuitive correspondence in the classical realm.

During the development of classical physics, such notions like particle, particle trajectories, point masses, or position and motion (momentum) of a particle were devised. The major developers of more recent times have been Newton, Euler, Lagrange or Hamilton. In parallel to this, the notion of a wave was developed – in particular in classical optics. Major representatives here were Huygens, Fraunhofer and Young. In the beginning of the 20$^{th}$ century, it became clear in physics – by Planck, Einstein, Bohr, Heisenberg, Schrödinger and others, that these physical concepts, which seemed to be complementary at first sight, could be unified on the scale of atomic matter. Matter can exhibit both wave and particle character. In quantum physics, notions like wave function, states, measurements, uncertainty relation and observables are used to describe wave properties of atomic matter. Those do, in the first instance, not have a direct counterpart in classical physics. For example, the wave function of a quantum system is not directly measurable, but is only a useful mathematical concept for the calculation of the probability of finding a quantum in a particular state after a measurement. Moreover, major notions of classical physics, such as position and momentum, acquire a novel quality in quantum physics. A classical particle can have at the same time an exactly known position as well as an exactly known momentum. Position and motion are thus two features of a classical particle which are independent from each other. A quantum particle, e.g. an atom or an electron, cannot – by principle – have an exactly known position, which is arbitrarily accurately measured, and at the same time have an exactly known momentum. Both are related to each other by the uncertainty principle. The more accurate one measures the position, the less accurate becomes the measurement result of the momentum. In this respect, position and motion of a quantum particle are inseparable properties.

From wave optics, we know that waves can interfere with each other, resulting in interference patterns. Those can be found in optical instruments or in the famous double slit experiment with light. Interferences require coherent waves, implying a necessary fixed common oscillation mode or phase relation between the individual oscillating waves. Two single sine waves have a fixed phase relation between each other, they oscillate coherently with a given phase. When many individual waves without a fixed phase relation superpose randomly, we see an incoherent result, as it occurs, e.g., on the surface of the ocean or of a large lake with weak wind. Many water waves superpose and an “incoherent soup” results. It is similar in optics: sun light originates in entirely disconnected electronic transitions in a large number of atoms, which yield incoherent light. It is only in the laser in which one can force the atoms by an electric field into a state of common coherent atomic transitions, by this forming coherent laser light. It is this externally enforced coherence which distinguishes laser light from natural sun light.

The example of the laser illustrates that rendering matter or light coherent requires rather large efforts from outside. Conversely, natural systems lose a possibly artificially created coherence rather quickly, because the very many subunits get rapidly out of phase due to many random fluctuations. This occurs in particular at higher temperatures and in systems with many particles, i.e., those of our everyday classical life. This are usually ‘out of phase’, while quantum mechanics requires to be in phase.

2. Pioneers of quantum physics like Pascual Jordan have already speculated that

quantum mechanics might also be relevant for biomolecules or processes in life. How do you judge these considerations from today's view?

Indeed, the pioneers of quantum mechanics have already asked themselves in the early times about the role of quantum physics beyond fundamental atomic physics, i.e., in the areas of chemistry or biology. Because matter in chemistry and biology consists of atoms and molecules, this question is obvious. It is undisputed that the elementary notions of quantum mechanics also apply there. When an X-ray photon hits a biomolecule and gets absorbed, this process follows the rules of quantum physics. When sunlight is absorbed by photoactive molecules and is transferred in photosynthesis, this occurs along the rules of quantum physics. Nobody questions this today.

But Pascual Jordan went a step further and formulated a biological holism or organicism in the tradition of German natural philosophy. He postulated already in 1932, that the question what brings living matter into life can be answered by the laws of quantum physics and its probabilistic interpretation. For this, the laws of quantum physics of randomness and probability should be up-scaled to the scale of biological systems within living organisms. His 'amplifier theory' was motivated by an extended correspondence with Nils Bohr. Jordan believed that living organisms perform an 'amplification' of the quantum mechanical indeterminism of the atomic world into the macroscopic world of biology. This should occur in a manner which would be fundamentally different from the inanimate matter. He even related quantum physics with psychology. During Nazi time, this biological view of Jordan as a supporter of the Nazi ideology got increasingly politicized and brought into accord with the prevalent ideology. He even formulated that the "Führer" principle would be a central cornerstone in the biology of life and that even every living cell would have a 'control center' as a dictatorial authority. Such abstruse proposals are fortunately history today.

But let me repeat: No one disputes today that the way of how biological and chemical matter is assembled and functions follows the principles of quantum physics. Yet, the question remains which of the many principles of quantum physics in chemistry and biology apply in nature.

3. A pioneering experiment of the proponents of quantum biology is presumed to be the paper by Engel, Fleming and colleagues published in Nature. It describes certain quantum phenomena of photosynthesis. What should one make out of this publication from today's view?

The scientific community has meanwhile accepted that the interpretation of the measured signals as long-lived quantum coherent electronic states no longer holds. Several control experiments at the Max Planck Institute for the Structure and Dynamics of Matter led by Prof. Dwayne Miller and with the collaboration of myself and by Prof. Donatas Zigmantas at Lund University in Sweden have shown that the observed signals, which by the way are rather weak, can be uniquely attributed to vibrational coherence of the molecules in the ground state. Many theoretical works meanwhile support this view as well. Ordinary oscillations are ubiquitous in molecular physics and can equally well be explained by the laws of classical physics.
In the meantime, this 'orthodox' interpretation of the experiments is accepted by the vast majority of scientists in the community.

4. A central aspect in the discussion is coherence. How can one visualize this, and is this notion really so intimately connected to the notion of 'quantumness' like the proponents of quantum biology believe?

'Coherence' as used in this context refers to the quantum mechanical coherence of the dynamics of electronic states in the light-harvesting biomolecular complexes. These complicated, large molecules consist of several photoactive subunits which carry these electronic states. When a solar quantum of light is absorbed in one region of the molecule (loosely spoken, 'in one corner of the molecule'), the excitation energy has to be transferred to the 'power plant' of the molecule, the so-called reaction center. This happens via a transfer between several other photoactive sites of subunits of the molecule. According to classical physics, this excitation could hop from site to site like a classical particle or be transferred through the network of sites like a quantum coherent particle quantum wave towards the exit. The latter mechanism requires though quantum coherence mentioned earlier. To maintain it

over a long time is almost impossible, given the numerous perturbations in the molecules caused on the one hand by the wiggling and dangling of the entire huge molecular backbone and on the other hand by the swirling, highly polar water molecules of the environment of the living organism. The original claim in the paper in Nature 2007 was that the required electronic coherence would be sufficiently long-lived to be functionally relevant for the biological processes. This has perplexed the scientific community the more so as it was known that the transfer overall occurs rather slowly on a time scale of picoseconds ($10^{-12}$ seconds), while any electronic coherence is commonly washed out on a one hundred times shorter time scale of a few 10 femtoseconds ($10^{-15}$ seconds). By our new experiments, we and other research groups have put this view back on the correct track.
It is undisputed that molecular nature follows the established principles of quantum physics. This concerns the 'usual' quantum physics. Certainly, it is tempting to claim that the 'quantum physics 2.0' expressed in the form of long-lived electronic coherence would be functionally relevant. In my eyes, this claim can no longer be perpetuated. No natural biological system is known which would follow this principle.

5. In your recent publication, you mention experiments which argue against a significant influence of quantum mechanics in photosynthesis. Which kind of experiments are they? What results did they deliver?

We do not claim that photosynthesis would not proceed under the rules of quantum mechanics. We only show that long-lived electronic quantum coherence does not exist and that, as a consequence, it cannot be used as a resource in photosynthesis. It is obvious that the transfer of excitation energy in photoactive light-harvesting complexes follows the basic principles of quantum mechanics.
The recent experiments use the same method as before, the two-dimensional optical ultrafast spectroscopy. By these experiments, one can track quantum coherence over time and make it directly visible. The recent experiments have shown that electronic coherence fades out within 60 femtoseconds at ambient environmental temperature of 300 Kelvin and that only an ordinary, but rather weak vibrational coherence survives. This has nothing to do with quantum mechanics though, but concerns the "wobble and dangle" of the molecular backbone. Our Swedish

colleagues have measured a decay time of 150 femtoseconds at lower temperature of 77 Kelvin, which is in agreement with our measurements. The decay of quantum coherence is thus approximately 14 times faster than claimed before, which is ages faster in the realm of biology. It is important to realize that this result shows the following: the fade out of quantum coherence occurs roughly 10 to 20 times faster than the transfer through the molecular network from initial light-harvesting to final utilization of the energy lasts. From this, we conclude that such a short-lived electronic quantum coherence cannot have any functional relevance in biology. Metaphorically speaking, an elephant tramping in the savanna for many days does not notice, when an ant on his back jumps coherently up and down for a few times.

6. Proponents like Martin Plenio from Ulm believe that quantum mechanics is imperatively necessary in order to explain the efficiency of photosynthesis. What is your position?

Natural photosynthetic systems have been optimized in the course of the evolution over millions of years. They have adopted to very different circumstances and boundary conditions, because they are parts of complex biological, biochemical and ecological systems. In my opinion, they had to optimize themselves in respect of much more important aspects, such as, for example, redundancy, energetically cheap reproducibility, survival strategies or insensitivity against ionizing radiation. In view of our experimental and theoretical results, utilization of quantum coherence is, from my point of view, rather not part of these aspects. Quite the contrary, nature requires the strong disturbance from outside in order to keep the electron as good as possible at its place where it is needed. The physicist call this ‘localization’. When the electron is quantum mechanically strongly blurred in space, the excitation energy it carries is rather useless for biology. For this reason, light-harvesting complexes rather use the external disturbances for an efficient localization instead of maintaining quantum coherence for a long time.

7. In my radio broadcast, I do not only discuss photosynthesis, but also the magnetic sensing of birds (www.quantumbirds.eu<http://www.quantumbirds.eu>) and the project "Quantum Brain" (www.kitp.ucsb.edu/mpaf/quantum-

brain<http://www.kitp.ucsb.edu/mpaf/quantum-brain>) of Matthew Fisher (UCSB), which looks for quantum effects in so-called Posner clusters for example in the brain. Your view of these approaches?

The theoretical concepts of using special quantum mechanical spin states in molecules for magnetic orientation by migratory birds are impressive and very well elaborated. When one compares these theoretical concepts with the real systems in nature, one finds unfortunately that the coupling constants in real systems are by a factor of up to 100 smaller than assumed in theory. However, magnetic spin states in molecules are in general rather immune against disturbance from outside. For this, I could imagine that it is most likely - if at all - that these concepts are realized in nature. Yet, a clear proof is still missing.
The concept of Matthew Fisher on the topics of Quantum Brain and quantum neural science is about an interesting hypothesis. Also there, spin states are at play, however, those of atomic nuclei. It is well-known that they can maintain their quantum coherence over quite a long time. Fisher himself is a very careful scientist though and calls his concepts “highly speculative at best”.

8. Do you consider the concept of quantum biology finally as failed and future research projects would be in vain? Or could there be reasons to still continue research in this direction?

This is a difficult question. Physics carries on by developing fascinating theoretical concepts, see for instance also in cosmology. In this respect, the enormous activities in these fields have generated certain progress in the understanding. An entirely different question is which of these theoretical concepts are realized in nature and find their application. In particular in the area of photosynthesis, I do not see that the concept of utilizing a long-lived electronic quantum coherence would be realized by nature, because coherence does at the very end not live long enough. It might be different in the field of spin states, because they are per se longer lived and less susceptible to disturbance from outside. As a matter of principle, it is always hard to aim to ‘steer’ basic research by guidelines. The most important findings of mankind have always been developed by questioning of seemingly established truths.

However, this can then only happen by the means of strictly scientific methods and has to demand in particular experimental verification by control experiments. In the field of quantum biology, they came rather late, yet science has the principal ability for self-correction.

Hamburg, 31 March 2020
Prof. Dr. Michael Thorwart