WHAT DOES A PHYSICIST DO AT WIKO?

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"What does a physicist do at Wiko?" This was the question Franco Moretti asked me when we first met. In one variant or other, the question popped up several times during the first few months. I don't think I ever gave a satisfactory answer back then. The best I can do at the moment is to describe what I regard as my accomplishments, with the hope that they shed some light on the question – at least in the case of this particular physicist.

My research field is low-energy physics: I investigate the properties of ultra-small solid-state systems at temperatures only a few degrees above absolute zero. In deciding to come to Wiko, I was convinced that I should use my time to learn about something completely new – an endeavour that would be very difficult in my home institution. I chose to study quantum biology – an emerging interdisciplinary field that aims at answering a prima facie intriguing question: are there biological processes that rely on quantum physics to enhance their efficiency, or are there functionalities that cannot be explained using classical mechanics?

The proposal I found particularly intriguing describes how migratory birds use quantum physics to sense the earth's magnetic field orientation, which in turn enables them to navigate. Together with Birgitta Whaley, we decided that we would study the proposal, termed magnetoreception, at length. While Birgitta and our guest Peter Hore were teaching me the basics of proteins incorporating optically active co-factors, two issues became clear to me.

The first realization has to do with the limits of interdisciplinary research: to prove a hypothesis such as magnetoreception requires a number of experiments utilizing vastly different experimental techniques, ranging from optical spectroscopy of single proteins, through chemical studies of signalling pathways, to behavioural studies of live migratory birds. In stark contrast to the usual problem-solving endeavours in our discipline, the physics or physical chemistry experiments that we would identify and implement cannot answer the overarching question in a conclusive manner. The same is true for the experiments that a biologist would carry out, and we do not even know where to start with a critical analysis of each other's experimental results.

The second and more important realization concerns the weakness of the definition of what quantum biology is. Our current understanding of all matter is based on quantum mechanics; this is particularly true for the structure and dynamics of molecules such as amino acids and co-factors that make up the proteins. A feature that distinguishes quantum physics from its classical counterpart is the possibility of finding a given system in a coherent superposition of its available states. According to the accepted paradigm of non-relativistic physics, classical dynamics emerges as a limit of quantum mechanics, when the system at hand interacts strongly with its environment. For time scales that are long compared with those governing this interaction, quantum coherence is lost and a simple classical description of the system in only one of the available states at any given time becomes accurate. Conversely, if we investigate the dynamics of any system on time scales that are short compared with those determining its coupling to the environment, we should find signatures of a coherent superposition of states. If all chemistry and biology are based on the implicit assumption of quantum coherence at short enough time scales, what does it mean to talk about quantum biology?

To address this conundrum, we developed a new description of a chemical or biological process as a quantum measurement. Typically, a quantum measurement describes information extraction about a quantum system by a classical meter. We turned this construction around to show that, when it comes to describing optically activated biochemical processes, the protein acts as a quantum meter designed to determine the properties of a classical input, such as the incident light intensity of the orientation of an external magnetic field. Remarkably, this counter-intuitive formulation allowed us to identify two different scenarios identified by the so-called commutation relation between the meter and the measurement Hamiltonian. In the first class of processes, the two Hamiltonians are not compatible (i.e. do not commute); when this is the case, the time scale over which quantum coherence survives has only a quantitative effect on the process. We argue that for this class, which includes the extensively studied photosynthesis, quantum coherence is circumstantial. For the second class of processes, in which the two Hamiltonians are compatible, the measurement interaction leads to different phases only for different quantum meter states. Extraction of this phase information requires an interferometric measurement, which is possible only if the quantum coherence persists on time scales exceeding those corresponding to the reciprocal energy difference between the meter states. In this case, the presence of quantum coherence makes a qualitative difference; without it, measurement is simply not possible.

At present, the only known biological process that falls into this interesting second class is magnetoreception. We nevertheless hope that our formulation will prove to be useful in seeking out and identifying other biological processes in which quantum coherence plays an essential role.

My discussions with our short-term visitors Peter Hore and Jörg Wrachtrup, as well as our local colleague Robert Bittl from FU Berlin, focussed mainly on the issue of identifying experiments that will allow us to determine the spin coherence time in cryptochrome – the protein that is believed to play the central role in magnetoreception. These discussions led me to design a single protein in a cavity experiment, which should not only allow us to determine the coherence time scales, but also to demonstrate the sensitivity of the protein to the orientation of the earth's magnetic field.

I have to admit that, during a sizeable fraction of my stay at Wiko, I did very little work on quantum biology! Instead, I worked on my German skills, read about the emergence of the nation state, learned early 20th-century Ottoman history, followed/analysed the demonstrations that shook Turkey and continued my usual research activity that I carry out jointly with Ph.D. students and postdocs in Zurich. Tuesday colloquia and the ensuing lunch discussions were truly enlightening for me, since they allowed me to learn about stimulating ideas and to see how the academicians in different fields formulated their questions. Overall, the year at Wiko was – *mit Abstand* – the most stimulating in my career.

Going back to the original theme of the essay, I could say that for this physicist, being a Fellow at Wiko meant meeting and befriending truly extraordinary people, exposure to a vast variety of ideas from the arts to the humanities and the opportunity to develop an original way of thinking about a problem that lies well outside his area of expertise. What more could he have asked for?