Il Colle di Galileo

Quantum Transport in Light-Harvesting Bio-Nanostructures

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Abstract. The one-day workshop "Quantum Transport in Light-Harvesting Bio-Nanostructures" was hosted at the Physics Department of Florence University on the 11th of March, 2013. It comprised both experimental and theoretical lectures by leading international exponents in research areas such as quantum transport phenomena, ultra-fast spectroscopy, natural and artificial light-harvesting complexes, quantum effects in biological photosynthetic systems, solar energy and information technologies. The goal was to spread the ideas of the new, strategically important and rapidly developing research area of Quantum Biology to the scientific community in Florence.

Keywords. quantum transport, photosynthesis, quantum biology, solar energy.

Introduction on Quantum Biology

The current alarming trends in global energy demand and the finite nature of conventional oil and natural gas reserves are inevitably pointing up the urgent need for the sourcing and timely development of new green energy systems.

According to the EU-US joint statement at the Lisbon Summit in November 2010, the EU-US Energy Council will be focused on "Green Growth", enhancing cooperation on the development and deployment of clean energy technologies and fostering participation by qualified researchers. In this context, a better understanding of natural photosynthesis could lead to the realization of new "Nature-inspired" devices. Indeed, one of the main obstacles is the difficulty of producing adequately efficient solar cells: single-junction (semiconductor) silicon devices are, for example, now approaching their theoretical efficiency limit of around 30%.

About 6 years ago fascinating experiments, based on ultra-fast spectroscopy techniques, showed that the explanation for electronic excitation energy transfer in light-harvesting complexes, involved in one step of bacterial photosynthesis, has to be sought in quantum physics, whereas classical mechanics cannot adequately explain the experimental data. In these biological systems, the efficiency

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of transferring sunlight energy to molecular reaction centers is extremely high (nearly 100%). Speed is the key: the transfer of solar energy takes place almost instantaneously and very robustly, so that little energy is wasted as heat. This also triggered several theoretical studies on how Nature exploits quantum coherence and environmental noise to implement such transport mechanisms. In particular, the presence of quantum effects seems to play a crucial role in this remarkably efficient, fast and robust electron energy transfer. Consequently, these experimental and theoretical investigations have led to a new, challenging, exciting, still young but very rapidly developing research field, namely *Quantum Biology*. It is expected to offer us a deeper understanding of the role of quantum physics in biological structures. The practical implementations of this in the 21st century could be crucial for novel, more efficient and powerful renewable energy nanotechnologies based on quantum phenomena.

Scientific Motivation

The leading international theoretical group on quantum physics led by Prof. M.B. Plenio, first at Imperial College, London (UK) and later at Ulm University (Germany), has played a fundamental role in this vibrant and cross-disciplinary field of research into "Quantum Effects in Biology", since its inception in 2008. One of its main research activities has been the analysis of quantum phenomena in photosynthesis and, more specifically, the analytical and numerical investigation of theoretical models describing energy/information transport in biological complexes and in quantum complex networks. This research has made several important contributions to explaining the basic key mechanisms underlying noise-assisted energy transport in biological photosynthesis. The organizer of the workshop was closely involved in this activity since its beginning and for several years while working in this group, before moving recently (as MIUR-FIRB PI) to Florence University (Prof. Inguscio's group). The main goal of his FIRB project (www.qubiot.com) is, indeed, to transfer the knowledge and expertise previously acquired abroad to launch this very exciting, emerging field of quantum biology in Italy, where research in this field does not yet exist. This highly interdisciplinary area brings together for the first time completely different research fields such as biology, atomic physics, quantum optics, chemistry, quantum information, and spectroscopy, for example, transversally, by applying different tools and approaches. This workshop was therefore particularly motivated by this objective; more specifically, the idea was to provide, mainly for the local scientific community in Florence, an open access, broad-audience workshop based on largely introductory lectures on this topic, from both theoretical and experimental angles, by the leading international exponents of this new research field.

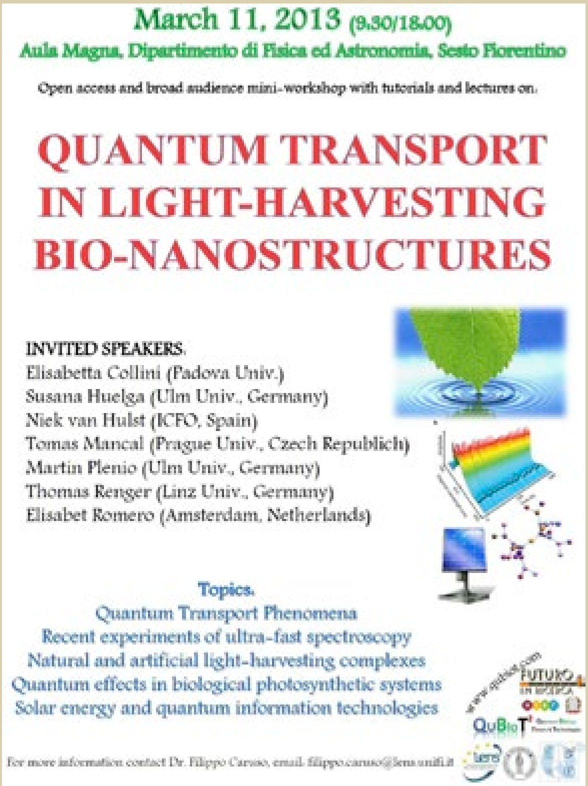
Filippo Caruso

The Workshop

The invited speakers came from six different EU countries for this one-day workshop on quantum biology that was financially supported by Dr. Caruso's FIRB-MIUR grant. In actual fact, it was the first event of a very intensive week of important scientific appointments in Florence, including the national CNR-INO Symposium and the QSTAR Research Center kick-off meeting.

Structure of the workshop:

- Experimental observations on quantum coherence in photosynthesis in 2008
- Crystal structures and theoretical modeling
- Principles of noise-assisted transport phenomena
- Role of environmental vibrational modes
- Experimental evidence of coherence in charge separation
- Theory of non-linear ultra-fast spectroscopy
- Experiments on single light-harvesting molecules
- Discussions of open issues in quantum biology



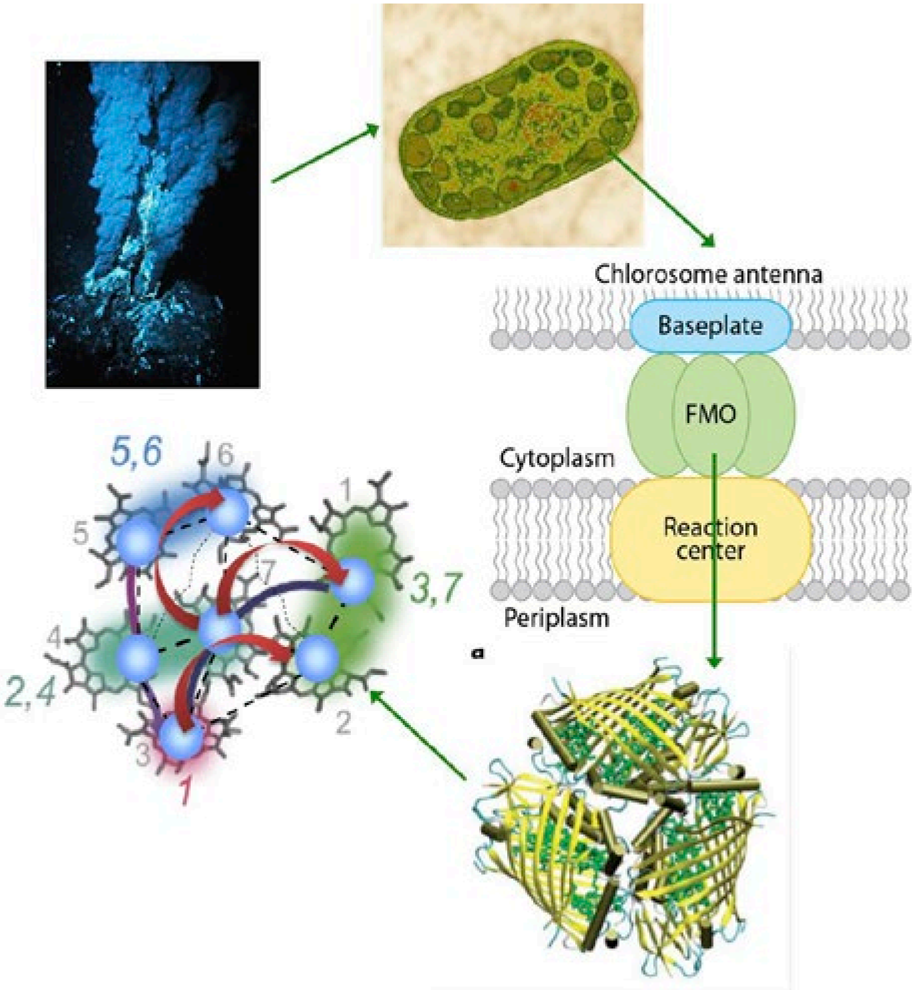


Fig. 1. Green Sulphur Bacteria are prototypes of light-harvesting systems, and probably the progenitors of life on Earth. They are even found living at the bottom of the Pacific Ocean where there is no sunlight and such pigment-protein complexes absorb about one photon every 24 hrs (thermal light), after which the generated electronic excitation is transferred to a reaction center (where the electron energy is converted into chemical energy) with the very remarkable efficiency of 99% in about 5 ps.

The meeting started with a lecture on the emergence of this new field around 6 years ago, as a result of some fascinating 2D ultra-fast non-linear electronic spectroscopy experiments on biological systems and polymers. This led to observation of the first strong evidence of the presence of quantum coherence, in the form of quantum beatings, in such energy transport dynamics. Later it was demonstrated how such experimental optical results could be matched with the crystallography structure data to build theoretical models on light-harvesting dynamics. After this, concepts of noise-assisted transport were discussed, as a first example of the beneficial interaction between electronic and vibrational degrees of freedom in biological systems. Indeed, the non-trivial spectral structures of the environmental fluctuations and particularly discrete vibrational modes appear to be responsible for the generation and sustenance of both oscillatory energy transport and electronic coherence, on timescales that are comparable to excitation energy transport. Hence, they revealed experimental evidence of the role of quantum coherence in understanding the mechanisms of charge separation in the presence of a highly disordered energy landscape. In addition to this, an introduction to the theoretical description of non-linear spectroscopy and the connection with modern issues of biophysics and quantum mechanics was also provided. Finally, there was a discussion of more recent experiments on quantum coherence, explored in this case at the level of individual light-harvesting complexes.

Outcomes and outlook

This workshop attracted a lot of attention and interest from the local community as well as scientists from all over Italy (around 80 participants); it triggered several interesting and stimulating discussions and generated several potential future collaborations, largely as a result of the participation of the most eminent experts in the field. The list of invited speakers, further details of the program, abstracts of the lectures and related scientific references are available at the workshop webpage http://lens.unifi.it/index.php?include=meetings&active=main&id=58.

Finally, the workshop also represented a very valid and successful test for the future organization in Florence of the official international conference on the topic (QuEBS 2015), which has to date been hosted by very prestigious institutions including Harvard, MIT, and UC Berkeley.