Quantum networks and their dynamics: a role in biology?

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1) Background and Aims of the project

Networking is an unavoidable tendency of our society. Every day we interact with different kinds of networks, often without noticing it. This occurs when we switch on the lights or check our Facebook accounts. Networks appear everywhere and in all aspects of human activity. In computer science, networks connect distant nodes where information processing is performed and allow the transfer of information from two such nodes. Networks are studied in mathematics in association with graphs that are categorized according to their connectivity, topology and structure.

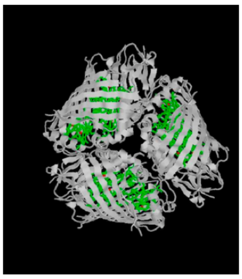

Figure 1: The FMO complex

"Links" are very common in biological processes. The way very simple organisms absorb, transport and elaborate the energy that they get from light is often very effectively explained by means of networks of some sort. For instance, the working principles of the so-called Fenna–Matthews–Olson (FMO) complex shown in Fig.1, which is one of the paradigm for such processes, are usually understood in terms of the motion of a quantum particle in a network consisting of seven sites, as shown in Fig. 2. This is an interesting example: the FMO complex is present in a tiny bacterium (the gree sulphur bacterium) which leaves in rather dark environments at hundreds of meters of depth in the sea, where only a scanty amount of light reaches it. Yet, it is able to make the most of such a tiny portion of energy! Very interesting recent studies, supported by preliminary experimental evidences, suggest that Quantum Mechanics may have a say in the efficiency and speed of such energy-transport process.

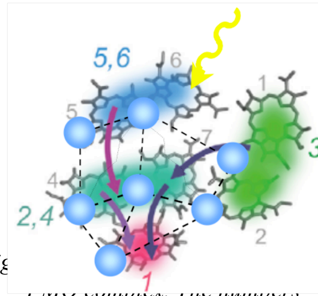

Fig ... the FMO complex. The numbers correspond to the seven sites of the equivalent network

Therefore, the key question that will be tackled by this project is: ***if Quantum Mechanics plays a role in biological processes, seemingly exploiting the working principles of simple networks, how has Nature evolved in order to optimize its use of the quantum lawsand improve the efficiency of its most fundamental processes?***

In order to answer this suggestive question, we will study "quantum networks", i.e. special types of arrays whose nodes are mutually interacting particles obeying the rules of Quantum Mechanics, and investigate their role in specific tasks of communication, transport and for the storage of information. We will ascertain whether properly tailored quantum processes, alegedly utilised by Nature in its master-plan of optimisation of biological processes, are indeed crucial for this. In particular, we will concentrate on the role that the geometry of a network plays in the optimisation of a given task: could it be that by changing the shape of a network, we are indeed able to perform a task in a better way? (*similarly to a football team that changes the configuration of its players on the pitch if they have to attack or defend*)
A positive answer to this question would mean that natural evolution appears to be the way through which these bio-complexes are found to have the shape we know. ***The project will thus use an evolutionary approach to the optimization of information exchange, storage and transport across quantum networks to understand Nature.***

Operatively, we will achieve this goal by means of the following multi-step strategy: **1)** *We will identify a task to perform (such as moving an excitation from one location to another) and an associated performance-gauging figure of merit*; **2)** *Wewill construct a network using a set number of sites and possible connections*; **3)** *If required by the task at hand, we will add external "influences" (such as lasers, voltage sources or magnetic fields) and sources of noise, errors and losses*; **4)** *We will compute the (quantum!) dynamics of the network. Our goal will be to optimize the figure of merit chosen to judge the quality of the network's performance.*

2) Supervision and Expected Collaborations

The project will be supervised by Dr. M. Paternostro (1st supervisor) and Dr. G. De Chiara (2nd supervisor) at the Centre for Theoretical Atomic, Molecular and Optical Physics, where they lead the Quantum Technology group (QTeQ). The student will be an important part of the team and will participate to the scientific activities of QteQ, including the delivery of journal club presentations and the attendance of special seminars by guests. More information on the composition of the team are available at http://www.am.qub.ac.uk/qo/.

The project will benefit of existing and new collaborations with world-leading groups in the field of quantum information, quantum biology and many-body systems. In particular we expect to strongly collaborate with top-notch research teams in UK, Germany, Spain and Singapore. The PhD student will be extensively involved in such collaborations by means of research visits and joint papers.

3) Technical aspects and required student skills

We are looking for a highly motivated, curious and ambitious student interested in the broad spectrum of quantum mechanical effects. Good marks in a course on introductory Quantum Mechanics are necessary, while knowledge of quantum information, biology or computer science is not required (although welcomed!).

Due to its multidisciplinary nature, the student working on this project will gain quite diversified competences, which will be highly beneficial to the development of their future career. Moreover, the student will be engaged in significant (yet very stimulating!) computational work, which is an important part of this project is very important. The student will learn how to design and write the numerical program for carrying out the necessary numerical simulations, possibly using open source numerical libraries for common tasks. This will be accompanied by a thorough theoretical study of the quantum mechanical processes at hand in such elementary biological processes, which will improve the analytical skills of the student.

4) Suggested Reading

An (incomplete) list of possible sources of additional information is given as follows

M. A. Nielsen and I. Chuang, *Quantum Computation and Quantum Information*, Cambridge University Press, 2000.
M. Arndt, T. Juffmann, V. Vedral, arXiv:0911.0155.
M. B. Plenio and S. Huelga, New J. Phys. 10 113019 (2008);
A. Olaya-Castro et al., Phys. Rev. B 78, 085115 (2008);
P. Rebentrost et al., New J. Phys. 11, 033003 (2009);
T. Scholak et al., Phys. Rev. E 83, 021912 (2011);
M. Sarovar, A. Ishizaki, G. R. Fleming, and K. B. Whaley, Nature Physics 6, 462 (2010).
R. E. Fenna and B. W. Matthews, Nature 258, 5536 (1975).
C.W. Gardiner and P. Zoller, *Quantum Noise*, Springer, 2000.

5) Requests for explanations and contacts

Potentially interested students are encouraged to contact Dr. De Chiara and/or Dr. Paternostro by email or telephone. A meeting to discuss the project and meet the QteQ members will be arranged with any interested student.