And what in fluctuating appearance hovers, ye shall fix by lasting thoughts. Goethe.

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Quantum effects in biology

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Abstract

The idea that quantum-mechanical phenomena can play nontrivial roles in biology has fascinated researchers for a century. Here we review some examples of such effects, including light-harvesting in photosynthesis, vision, electron- and proton-tunneling, olfactory sensing, and magnetoreception. We examine how experimental tests have aided this field in recent years and discuss the importance of developing new experimental probes for future work. We examine areas that should be the focus of future studies and touch on questions such as biological relevance of quantum-mechanical processes. To exemplify current research directions, we provide some detailed discussions of quantum-coherence in photosynthetic light-harvesting and highlight the crucial interplay between experiment and theory that has provided leaps in our understanding. We address questions about why coherence matters, what it is, how it can be identified, and how we should think about optimization of light-harvesting and the role coherence plays.

Keywords: quantum biology; photosynthesis; excitation energy transfer; long-rangel electron transfer; H-tunneling

Introduction

As noted by Erwin Schrödinger in his famous book "What is Life?" [1] quantum mechanics accounts for the stability of living things and their cellular processes through our understanding via quantum mechanics of the stability of molecules, and the fact that quantum effects create, sometimes large, energy gaps between different states of chemical systems. These same energy gaps when applied to electronic energy levels enable living things to capture and store the energy carried from the sun by photons, and to visualize the world around them via optically induced chemical reactions. Davydov's view in "Biology and Quantum Mechanics" [2] was that quantum mechanics is most relevant for isolated systems in pure states and therefore is of little importance for biological systems that are in statistical states at thermal equilibrium.

The focus of this article, and in the biologically oriented portion of this Solvay Conference, is not on the well known role of quantum mechanics in equilibrium systems, such as molecular structure and stability, but in exploring the potential role of quantum effects in dynamical processes of importance to living things. Such effects may derive from quantum interference, from functionally important quantum superposition states, tunneling of light

particles such as electrons or H atoms, and possibly from non-local effects encompassed by the general concept of entanglement.

Many of the quantum phenomena listed in the preceding paragraph are generally regarded as exceedingly delicate and not likely to survive for relevant timescales in "warm, wet and noisy" living things. Thus, the experimental observation by Engel et al of long-lived quantum electronic coherence in a photosynthetic light harvesting protein [3] produced widespread interest [4-8]. The initial experiments were carried out at 77K, but subsequent work by Scholes and co-workers [9] and Engel and co-workers [10] confirmed the persistence of the quantum coherence at physiological (room) temperature. Such studies involve femtosecond-duration laser pulses. The relevance of the coherent phenomena observed in such experiments to the behavior of systems illuminated by sun – or even moonlight – requires careful clarification. It might be worth saying that while experiments are carried out with coherent excitation (a) the underlying Hamiltonian probed by these experiments is the same Hamiltonian that governs the dynamics under sunlight illuminations. We discuss our views on the interpretations of these experiments in Section 4.1. (b) a key point is that the simulations inspired by these experiments do not need to assume coherent excitation, and it is really these simulations that ultimately gives us insight about how coherences modify the dynamics.

One of the most prominently recognized debates of a possible role played by quantum mechanics in biology is that concerning brain function. Hameroff and Penrose have hypothesized that quantum-mechanical superposition states of microtubules can rationalize brain activities leading to thoughts, feelings, sense of self, and transitions of consciousness [11]. Tantalizing questions have been examined that work. For example, the abrupt transition to unconsciousness caused by anesthetic drugs [12]. Nevertheless, the arguments presented so far have not been supported by experimental studies [13,14]. In this article, we will confine ourselves to phenomena whose fundamental aspects are susceptible to a combination of experimental and theoretical investigation at a reasonable level of precision and sophistication.

Potential Quantum Dynamical Processes in Biology

	Excited States	Light Particles	Radical Pairs
Biological Phenomena	Primary steps in photosynthesis Vision	Enzyme catalysis Photosynthesis	Bird navigation
Quantum Processes	Energy transfer Electron transfer Isomermization	Long-range electron tunneling H atom transfer Proton-coupled electron transfer	Reactions producing radical pairs

Fig.1. Potential quantum dynamical processes in biology.

Figure 1 lays out the elementary processes underlying the phenomena we will discuss, while the context of those processes in specific biological phenomena is given in the lower portion of the figure. Many other phenomena could be included, but those specified in Figure 1 are, in our opinion, the most suited to rigorous exploration at the present time. In Section II we describe the key quantum aspects of the processes and phenomena considered. Detailed descriptions of the phenomena and the current status of theory and experiment can be found in other articles in this volume. Photosynthetic light harvesting can be considered as the paradigmatic model for quantum effects in biological systems and is also to the subject of experimental investigations.Therefore, in this article we place most emphasis on experiment and theory for photosynthetic excitation energy transfer in this article. In

Section III we briefly sketch the experimental and theoretical methods used to study the phenomena. In Section IV we attempt to formulate the key questions that arise based on our current understanding. Finally in section V we discuss what developments might be needed to advance the understanding of the role and significance of quantum effects in biology, and to realize synthetic devices inspired by our understanding of quantum biological function.

1. Key Quantum Aspects of the Phenomena Considered

In 1962, Longuet-Higgins wrote in his paper titled "Quantum Mechanics and Biology" that quantum mechanics only helps us to understand a few biological processes that involve radiation [15]. Active researches since then have revealed that this rather conservative view requires modification. Indeed, quantum phenomena in biological systems that require explicit reference to the quantum theory abound, and in this section, we briefly describe the quantum aspects of these phenomena to show that non-trivial quantum mechanical effects play important roles in many biological functions.

We begin by distinguishing between phenomena where the detailed dynamics of the process are susceptible to experimental and theoretical investigation, and those in which only overall rates are observable and the challenge is to explain the magnitudes and trends found in experiment. The recent development of two-dimensional electronic spectroscopy has placed photosynthetic light harvesting in a unique position for the investigation of quantum dynamical phenomena in biological systems. Accordingly this topic has seen considerable recent development and much of our discussion of the key questions and developments needed in Sections IV and V will center on natural light harvesting.

1.1. Photosynthesis

Light harvesting in photosynthesis is the paradigmatic model for quantum effects in biology. Photosynthetic pigment-protein complexes collect sunlight and transfer the energy in the form of electronic excitation to the reaction center for charge separation that drives biochemistry. Light harvesting processes in photosynthetic organisms exhibit remarkable quantum efficiency, usually > 95%, therefore it is of great research interest to investigate the design principles of this extremely efficient process. The success of natural light harvesting depends on ultrafast excited state dynamics including energy transfer and charge separation, where quantum superposition and coherence dynamics play important roles. Thus, models based on the quantum theory are crucial for the understanding of the primary process of photosynthesis.

In photosynthetic complexes, pigment molecules are packed together, arranged so that couplings between their electronic transitions are significant. As a result, optical excitations of a photosynthetic complex are described by the Frenkel exciton model that considers the following effective Hamiltonian for a system made of N chromophores:

$$H_e = \sum_{n=1}^{N} \varepsilon_n |n\rangle\langle n| + \sum_{n<m} J_{nm}\left(|n\rangle\langle m| + |m\rangle\langle n|\right) \qquad (1)$$

where $|n\rangle$ is a molecular excited state of the n-th chromophore, ε_n is the transition energy of the molecular excited state (site energy), and J_{nm} is the is the excitonic coupling between the transition dipoles of the n-th and m-th chromophores. These excitonic couplings are crucial for excitation energy transfer. Furthermore, when excitonic couplings are significant, the energy eigenstates that diagonalize the Hamiltonian have to be considered to describe the optical properties and excitation energy transfer within the complex, leading to the so-called exciton basis. Excitons are normally quantum superposition of multiple molecular excited states within the complex. As a result, a photon that is absorbed in a light-harvesting complex produces a collective excitation in the complex. It was realized rather early that the picture of photosynthetic excitons is necessary for the understanding of the spectroscopy and dynamics of photosynthetic complexes [16,17]. For example, excitons play important roles in defining the energy landscape in the Light-Harvesting system 2 (LH2) from purple bacteria and also strongly influence the electronic energy transfer dynamics in the system.

A less well understood quantum aspect of photosynthesis is the excitonic coherence effect that is due to superposition of exciton states. It is instructive to write down the time evolution of the wavefunction of a quantum superposition state of two excitons:

$$|\Psi(t)\rangle = c_1 e^{-i\omega_1 t} |e_1\rangle + c_2 e^{-i\omega_2 t} |e_2\rangle \qquad (2)$$

where $|e_1\rangle$ and $|e_2\rangle$ are excitons, and $\hbar\omega_1$ and $\hbar\omega_2$ are their energies, respectively. The density matrix in terms of these pure states is then:

$$\rho(t) = |\Psi(t)\rangle\langle\Psi(t)| = \begin{pmatrix} |c_1|^2 & c_1^* c_2 e^{-i(\omega_2-\omega_1)t} \\ c_1 c_2^* e^{i(\omega_2-\omega_1)t} & |c_2|^2 \end{pmatrix} \qquad (3)$$

The diagonal density matrix elements, i.e. populations, are stationary against the coherent excitonic Hamiltonian dynamics, and the quantum dynamics are fully manifested in the phase evolution of the off-diagonal density matrix elements, i.e. coherences. As a result, coherent wavelike dynamics depend on the existence of the excitonic coherence. Note that coherences in the exciton basis are special because of this dynamical aspect. Here we refer to coherence between exciton states as excitonic coherence.

In a condensed-phase environment, particularly in biological systems, excitonic coherences are often considered *a priori* to decay rapidly and therefore can be neglected. However, the development of the two-dimensional electronic spectroscopy has demonstrated excitonic coherence effects lasting for a time scale comparable to the time scale of excitation energy transfer in photosynthetic complexes at both 77K and ambient temperatures, indicating coherent dynamics and excitonic coherence effects have to be considered explicitly in order to adequately describe photosynthetic light harvesting.

1.2. Long-range electron transfer

Not long after the birth of the quantum theory it had been realized that the new physics allows a particle to pass through a barrier that is classically insurmountable. A particle tunnels through a square potential wall with a transmission coefficient κ that decays exponentially with increasing tunneling distance r:

$$\kappa \propto e^{-\frac{2}{\hbar}\sqrt{2m\Delta E}\cdot r} \qquad (4)$$

where the decay constant is determined by the square root of the product of the mass of the particle times the height of the potential well ΔE. Equation (4) indicates that light particles can tunnel through a potential barrier effectively to achieve reactions that are forbidden in classical mechanics. In addition, the dependence on ΔE means that by effectively reduces the potential barrier, the tunneling mechanism can be more favored. In biology, this implies that electrons and protons can participate in reactions through tunneling. In biological systems, tunneling involving transfer of light particles (hydrogen or electrons) provides an alternative route to classical over-the-barrier reactions, resulting in a significant increase in the reaction rate or a way to direct electron transfer through proteins.

Tunneling in biological systems was first reported in electron-transfer reactions in proteins [18,19]. Electron flow between distant redox-active cofactors is a common phenomenon in aerobic respiration and photosynthesis, and it regularly occurs between molecules separated by more than 15 Å in proteins. Such long-range electron transfer in the biologically relevant time scales of milli- to micro-seconds plays key roles in the energy transduction pathways of life. Investigations on ruthenium-modified proteins carried out by Gray and coworkers in the past two decades have yielded a remarkably detailed description of the distance- and driving-force dependences of long-range

electron tunneling rates in proteins [20,21]. Experimental observations of weak temperature dependence in rates and exponential decay of the transfer rate as distance increases indicates that these long-range electron transfers in proteins occur by single-step electron tunneling across a long distance, in contrast to a multistep hopping mechanism. Through a superexchange-mediated mechanism, the protein medium provides low-lying electronic states that results in significantly higher electron tunneling rates, usually > 10 orders of magnitude higher compared to similar distances through vacuum. Theoretical analysis based on the *pathways* approach revealed specific channels for electron transfer in proteins through covalent bond, hydrogen bond or even van der Waals contacts [22-24]. It is intriguing to consider that proteins provide efficient electron conduction pathways to facilitate electron transfer [25-28], however, Dutton and coworkers have shown that an empirical model based on average protein density, effectively treating the protein as a structureless random medium, also explains the experimental data [29-31]. Whether or not the electron conducting proteins have evolved efficient pathways for electron transduction is still an open question.

The quantum theory also predicts that electron transfer pathways could exhibit interference effects [22]. A detailed theoretical analysis of electron transfer through the azurin protein carried out by Regan and Onuchic suggested that quantum interferences between multiple distinct pathways play important roles in this protein [22,32, 33]. However, definite experimental evidence for the quantum interference effects in long-range electron transfer in proteins remains elusive [21].

1.3. H-tunneling

In many enzymatic catalytic reactions, the rate-determining step involves the transfer of a proton, hydride, or hydrogen atom [34]. In addition, the simultaneous transfer of a proton and an electron from different sites (so-called proton-coupled electron transfer) also play an important role in a wide range of biological functions [35,36]. In these enzymes, quantum effects could contribute significantly to the catalytic rates because of the energy shift due to the zero-point energy that gives a quantum correction to the classical activation free energy and the H-tunneling effects [34,37,38]. Such nuclear quantum effects represent another class of quantum phenomena in biological systems.

Nuclear quantum effects in enzymes have been studied via measurements of the intrinsic kinetic isotope effects (KIE) in enzyme catalytic reactions [39-41]. For example, H/D KIEs close to 100 have been measured in methane mono-oxygenase [42] and soybean lipoxygenase [43], and the sizes of the KIEs clearly indicate quantum-tunneling effects. Moreover, in many other enzymes, H-tunneling was also conclusively demonstrated through a careful analysis of both the primary and secondary KIEs [37,44]. Clearly, enzymes have evolved to attain preorganizations of active sites and subtracts that can take advantage of H-tunneling to achieve increased reaction rates. Note that Marcus-like models including environmentally coupled H-tunneling have been shown to provide adequate descriptions of H-tunneling in enzymes [45-47].

The short de Broglie wavelength of the nuclear wavefunction of a proton makes H-tunneling extremely sensitive to distance fluctuations, leading to potential strong coupling between protein motions and the H-tunneling kinetics. A hotly debated issue in enzymatic catalysis is whether or not the couplings to slower protein dynamics serves to control the quantum tunneling events and contribute to an increase of the catalytic reaction rate [48,49]. Such "gating dynamics" have been proposed to explain the anomalous temperature dependent KIEs in several enzymes. Nevertheless, we will focus our discussions here on the quantum aspects, and the topic of classical gating dynamics in enzymes is outside the scope of this conference.

1.4. Magnetoreception

There is compelling evidence that numerous organisms, including magnetotactic bacteria, insects, amphibians, birds, fish, sharks and rays, and some animals orient themselves using the earth's magnetic field [50-53]. It has been shown, for example, that homing pigeons can be trained to recognize a weak magnetic anomaly [54]. Their response after training can be upset by attaching a magnet to part of their beak known to contain a biogenic magnetite body, suggesting that this structure—also found in the organisms mentioned above—is involved in sensing the magnetic

field. The identification of such a structure as biogenic single-domain magnetite in olfactory lamellae of rainbow trout has been reported [55]. Other studies have established how the magnetic field lines are sensed in order to derive direction [56,57].

One hypothesis for the mechanism underlying magnetoreception is that the magnetite bodies (arranged as an oriented string) are coupled to special receptors so that mechanical torque in response to magnetic field changes activates an ion channel to initiate signaling [58,59]. This hypothesis explains the presence and use of the chains of magnetic bodies that have been clearly identified, but precisely how the signalling happens is unknown. How the light-dependence of some magnetoreception behavior (see below) fits with this mechanism has not been adduced, but it has been argued that the involvement of light-activated steps does not preclude the involvement of mechanical action [60].

In some studies it has been found that magnetoreception, at least in the case of newts and birds, is light-dependent [61]. This work strengthened a second hypothesis for the mechanism of magnetoreception whereby a light-initiated chemical reaction [62], possibly occurring in a cryptochrome photoreceptor [63], is tuned by changes in magnetic field [64]. Changes in rates of a reaction involving radical pairs [65] caused by changes in magnetic field orientation are suggested to provide magnetic field transduction [66]. The strength of this model is that, in principle, the mechanism can be highly sensitive to magnetic field changes. A substantial amount of experimental evidence shows that the light-dependence includes wavelength specificities and is evidently complex [67,68].

The magnetic sense has obvious biological relevance because it aids navigation, orientation, and long-range migration, but is the underlying mechanism quantum-mechanical? The answer depends on which mechanism is ultimately found to underpin magnetoreception. The first mechanism described above is based on classical electromagnetism and can therefore be anticipated without resort to quantum mechanics. The second mechanism builds on the idea that ladders of electronic states are prevalent in biological examples of quantum mechanics, but in this case those ladders, specifically the relative energies of singlet and triplet states, are used to sense an external stimulus. The possibility that biological systems are performing a kind of magnetic resonance experiment to guide their seasonal migration patterns or other navigation is fascinating. Crucial advances, however, are needed to obtain compelling experimental connections between behavior of the organisms and the molecular level mechanisms underlying the traits.

2. Methods of Study

2.1. Experiment

How can experiments be designed in order to reveal evidence for quantum-mechanical processes in biological systems? This is a critical question because the field of quantum biological is based largely on theoretical predictions, and these must be tested to confirm or challenge them. Photosynthetic light-harvesting provides a good example (perhaps the only one in this field) of this process. Researchers have studied the light-harvesting process in photosynthesis for many years using sophisticated experiments that employ pulsed lasers to inject excitation energy into a pigment-protein complex and time subsequent events against a clock set as a the delay time between the laser pulse that excites the system (the "pump") and one that is used later to probe the state of the system. In this way the dynamics of energy transfer can be followed on a femtosecond time scale. For example, we can work out how fast energy is transferred among light-absorbing molecules in photosynthetic antenna proteins. Do these kinetic data provide sufficient information to challenge or inspire theories for energy transfer? In general they do not. First, theoretical models for energy transfer in such complex systems cannot be formulated with sufficient precision that prediction of energy transfer timescales provide a metric for deciding the validity of a theory. Second, often timescales or efficiencies of energy transfer are weakly sensitive to the mechanistic model for energy transfer [69, 70]. That means that experiments need to be designed that ask questions about mechanism, not the rate, of energy transfer.

Two-dimensional photon echo spectroscopy (2DPE) provides researchers with a means not only to measure timescales of energy transfer, but also to detect the pathways through which energy flows. These 2DPE experiments are able to elicit some mechanistic details about energy transfer, and in particular they have revealed evidence for quantum-coherent processes that assist the transfer of energy. Evidence that quantum dynamics is involved in light-harvesting is seen by the behavior of cross-peaks in the 2DPE spectra, which rise and fall in amplitude out of phase with each other as a function of time delay between pump and detection, like two pistons in an engine, Fig. 2. As a result of this experimental scheme for finding quantum-coherence in energy transfer, theoretical investigations have made enormous progress and we are on the point of gaining important and deep insights into this difficult problem.
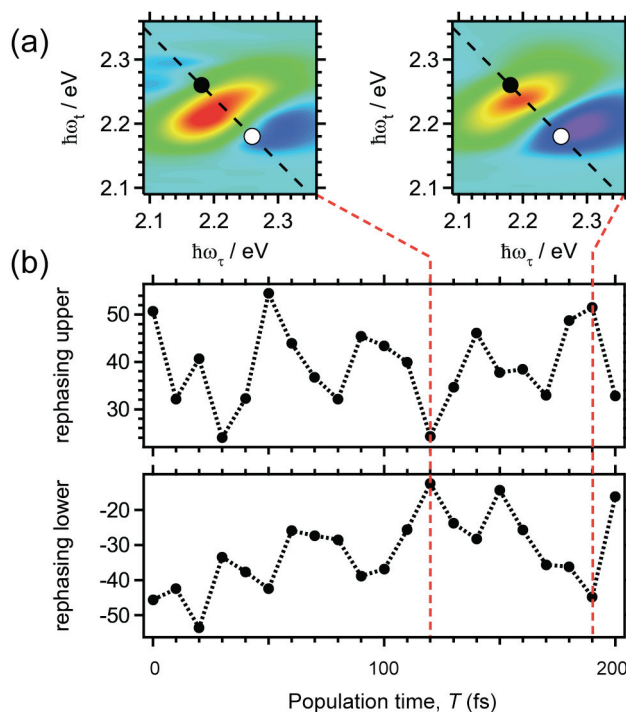

Fig.2. (a) 2DPE spectra for the marine cryptophyte alga *Rhodomonas* sp. strain CS24 light-harvesting antenna protein PE545 (294 K). The population times are indicated by the red dashed lines connected to the plots in part (b). The circles on the spectra indicate the location of crosspeaks; (b) The amplitude oscillations of the crosspeaks are plotted as a function of population time, showing how the upper and lower crosspeaks beat out of phase.

2.2. Theory:

The exciton Hamiltonian given in Eq.(1) provides a zero-th order description of optical excitations of a photosynthetic complex. In order to calculate the dynamics of excitation energy transfer, the protein environment and solvent that modulate the electronic excitations and give rise to relaxation must be included in the theoretical model. It is reasonable to consider the molecular excitations coupled to a harmonic bath through a linear system-bath coupling Hamiltonian:

$$H_{SB} = \sum_{n=1}^{N} |n\rangle\langle n| \cdot q_n \qquad (5)$$

where q_n is a collective bath coordinate coupled to the n-th chromophore. Within this model, the dynamics is related to the spectral density, $\Omega_n(\omega)$, which describes the density of states and coupling strength of the phonon bath as a function of phonon frequency. The strength of the system-bath coupling is measured by the bath reorganization energy

$$\lambda_n = \int_0^\infty d\omega \Omega_n(\omega) / \omega \qquad (6)$$

This system-bath model provides a microscopic basis to calculate various spectra and the dynamics of excitation energy transfer in photosynthetic complexes.

Two perturbative limits of excitation energy transfer dynamics can be identified in the theoretical model: In the small excitonic coupling (J_{nm}) limit, a description based on the localized donor and acceptor excited states is appropriate, leading to the Förster picture of energy transfer. Conversely, when the system-bath coupling is weak (i.e. $\lambda \ll J$), a delocalized excitonic representation is needed, which leads to the Redfield equations. These theories have been broadly adopted, and adjusted, to describe photosynthetic light harvesting in their respective applicable regimes. The classic Förster theory has been generalized to include more realistic models of excitonic couplings and coherence effects within donor or acceptor subunits. The modern multichromophoric Förster resonance energy transfer theory considers donor and acceptor each as a small group of molecules that are coherently excited and dynamics of incoherent hopping between these groups, which seems to provide a satisfactory description for the dynamics of energy transfer in energetically well-separated components such as the LH2 complex of purple bacteria [71-75]. On the other hand, Redfield theory considers relaxation between delocalized exciton states. Yang & Fleming examined the limitations of the Redfield formalism and proposed a modified Redfield approach that treats strong system-bath coupling and multiphonon processes, which is important for systems with large energy gaps or at low temperatures. The readers are referred to previous reviews of the developments and respective limitations of these perturbative methods [76-78].

Perturbative theories, however, were challenged by more recent experimental observations. For example, the observation of long-lasting quantum coherence in the FMO complex clearly requires a more general theoretical description that includes the effects of a non-local correlated bath, coherence transfer dynamics, and non-Markovian dynamics. The limitations should not come as a surprise, because in most photosynthetic complexes, the excitonic couplings and bath reorganization energies are both on the order of a few tens to a hundred wavenumbers. Effectively the excitation energy transfer dynamics are in the intermediate coupling regime, and therefore the perturbative treatments are inadequate. These new experimental data have motivated much theoretical effort. For example, Jang et al. adopted the small-polaron representation that was popular in condensed-matter physics to develop a theory for coherent energy transfer that interpolates between the Förster and the Redfield limits [79,80]. In addition, Ishizaki and Fleming have applied a nonperturbative reduced hierarchy equation approach to investigate coherence dynamics and temperature effects in photosynthetic energy transfer [81,82]. Their results have helped to gain much insight about the dynamics of light-harvesting including temperature-dependence of coherent dynamics [83,84], the roles of entanglement and coherence [4,85-87], and the importance of non-equilibrium bath effects due to the tight coupling between the rapid sub-ps excitation transfer and the bath reorganization dynamics [83]. Finally, nonperturbative path-integral based approaches [88-92] that were successful in treating the spin-boson problem have been applied to study coherent excitation transfer in photosynthesis recently [92,93].

3. Key Questions

3.1. Is Coherence Important?

We first need to define what we mean by coherence. In light harvesting we mean coherence between exciton states, which implies the wave-like character of energy flow. In the site basis the presence of long-time or steady

state coherence simply means that the eigenstates of the system are delocalized (exciton) states. The fact that electronic coherence is observed via an ultrafast spectroscopic method which creates initial coherence and records its loss as a function of time has created a certain amount of confusion regarding the significance of coherence in natural light harvesting. A typical question might be: " Does the coherence only matter during the first few hundred femtoseconds of the energy transfer following the absorption of light?" In our view the basic premise of this question is incorrect. The ultrashort pulse excitation simply serves to coordinate the ensemble in time and allow observation of dynamical processes which, through theoretical modeling, enable deductions about the system's Hamiltonian. The observed coherence in the ensemble decays by two mechanisms. The first is ensemble dephasing, that does not destroy coherence in individual complexes, but disrupts the correlation between the oscillatory behavior of individual members of the ensemble leading to the decay of observable oscillations in an experiment. The second is microscopic dephasing, or decoherence, that destroys the coherent superpositions between excitons in an individual complex.

We currently lack both experimental and theoretical methods to observe and characterize microscopic dephasing in the condensed phase. Nontheless because we expect the fluctuations within an individual complex to be uncorrelated with those in other members of the ensemble we expect the microscopic dephasing to be significantly slower than the ensemble dephasing. Indeed it seems reasonable to suggest that that the system-bath interactions create and recreate coherence throughout the energy flow process. However, in an ensemble measurement, different members of the ensemble rapidly (in a few hundred femtoseconds) become uncorrelated and the coherence is not directly observable. Both dephasing processes contribute to the decay of oscillations that is measured in two-dimensional electronic spectroscopy. This is illustrated, at the ensemble level, in Figure 3 which shows a calculation based on the reduced hierarchy model of Ishizaki for the FMO complex. The quantity plotted, the concurrence, quantifies the coherence between given pairs of BChl molecules (i.e. the picture is in the site basis). The system, which is initially prepared with all the population on BChl 1, starts with no coherence and as time progresses coherence develops not just between Bchl 1 and other BChls (e.g. BChl 2) but also between pairs of BChl (e.g. BChls 3 and 4) which are only populated via energy transfer. The oscillations indicate wave – like energy transfer while the long time coherence shows that the energy eigenstates of the system are delocalized, typically over pairs of BChl molecules. Note that all the coherence developed in this example comes from the action of the system-bath Hamiltonian and does not involve any system-radiation field term.

To sum up the previous paragraph: coherence is present at all times and is continuously being created, destroyed, and recreated by the interaction of the electronic system with the surrounding nuclear degrees of freedom. The picture referring to stationary eigenstates is a result of coarse-graining via a convenient mean-field approximation. The wavefunction of an electronic excitation in a photosynthetic complex is never stationary, perpetually evolving under the influence of the fluctuations in its condensed-phase environment. These environmental fluctuations modulate the energy and couplings of the collective molecular system and lead to dynamical transitions of excitation energy transfer. This physical picture underpins all quantum dynamical processes in the condensed phase.
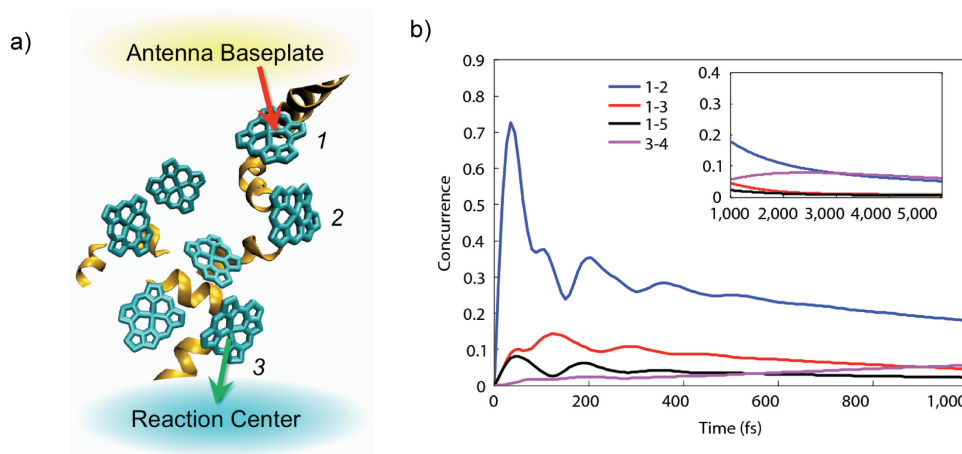
Fig.3. Bipartite entanglement in the FMO protein when the initial state is an excitation localized on site 1. The figure shows the time evolution of the concurrence measure of bipartite site entanglement, $C_{ij}=2|\rho_{ij}|$, at 300 K. Only curves for the most entangled chromophores are shown. The insets show the long-time behaviour. The simulation was carried out using the reduced hierarchy equations approach developed by Ishizaki and Fleming. The details are described in Ref.[4]. Reprinted by permission from Nature Publishing Group. Originally published in [4].

Finally, for coherence to play a role it is still important that the relevant process occurs in a short time scale, because otherwise microscopic dephasing (decoherence) would be complete before population transfer has occurred. These considerations are directly relevant to recent discussions of the nature of photosynthetic energy transfer and other ultrafast optical biological processes such as vision under solar radiation.

3.2. What Use Is Coherence?

Having established the existence of coherence in light harvesting complexes, the question naturally arises as to whether this coherence brings any advantages or new functions to the photosynthetic apparatus. Our perspective will be that coherence provides a tool to enable optimization for a range of specific functions. One way to approach the question posed above is to note that at low light levels photosynthetic light harvesting operates at very close to 100% quantum efficiency in delivering absorbed energy to the primary electron donor in the reaction center. What problems need to be solved to achieve this remarkable efficiency?

First, following the absorption event, a clock starts whose duration is set by the excited state lifetime of the chromophores (generally chlorophylls (Chls) or bacteriochlorophylls (BChls)). In array sizes of 200 – 300 Chls a simple calculation suggests a transfer time of 50 – 100 fs will be required to achieve > 95% efficiency for a fluorescence lifetime of 2 ns. Thus very rapid energy transfer is necessary. In this case too much or too little coherence will produce non-optimal rates of transfer, as is easily seen from the following argument: If the system is fully coherent it will simply oscillate and no population transfer will occur. On the other hand if the coupling to the environment (reorganization energy) is large and rapid enough to completely localize the energy, the rate will also be zero since population will be unable to leave the initially excited state. We can therefore clearly expect a maximum in the rate between these two extremes. Figure 4 compares, for a dimer system, the formally exact result of Ishizaki and Fleming with two standard perturbative approaches – Förster theory, valid in the limit of large reorganization energy and Redfield theory, valid for very weak environmental coupling. As noted in Section III, because the timescales of energy transfer are so short, it is important to include an appropriate timescale for relaxation of the environment (bath). Finally, in the example shown, the parameters were selected to minimize coherence so as to enable a clear definition of the " rate". Also note that the maximum rate is smaller than that obtained from Förster theory making questions such as " Do quantum effects speed up energy transfer?" ambiguous

at best. To sum up, the optimal timescale of energy transfer requires a balance between electronic coupling induced coherence and dephasing via interactions with the bath.
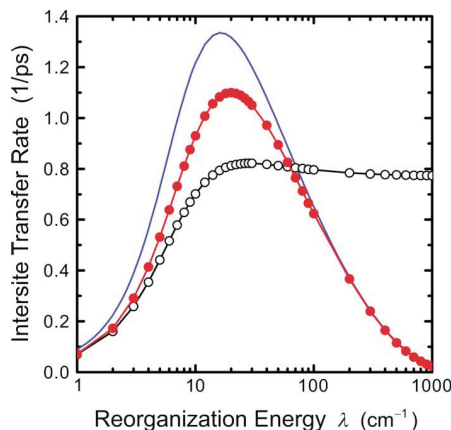

Fig.4. Intersite energy transfer rates in a dimer model as a function of reorganization energy predicted by Ishizaki and Fleming's reduced hierarchy equation approach (closed circles), the full-Redfield equation (open circles), and Förster theory (solid line). Reprinted by permission from American Institute of Physics. Originally published in [82].

What control knobs are available to optimize light harvesting? Figure 5 describes the three main control parameters, what out comes their variation can produce, and the underlying mechanism of these new functions.
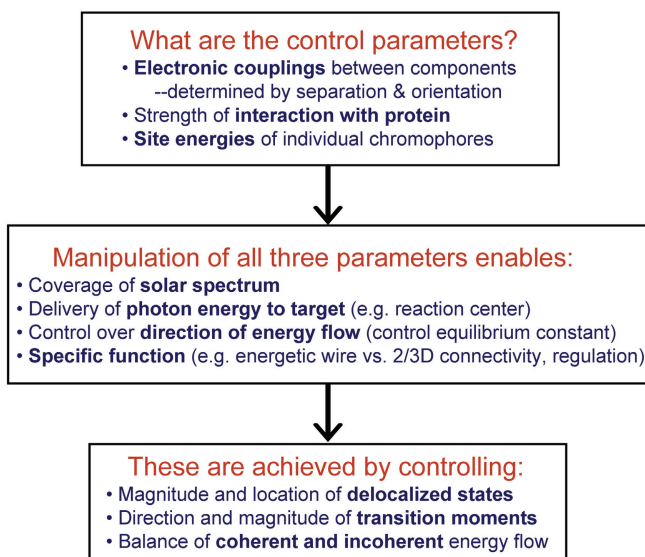

Fig.5. Strategies for optimizing light harvesting.

Second, coherence can help delocalized excitations to avoid trapping by local energy minima on the large and rugged energy landscape of a photosynthetic system, in which an incoherent hopping mechanism would require the excitation to sit on each one of the local minima along a energy transfer pathway and wait for slow thermal activated event to complete transfer. Coherence, which is indicative of a non-equilibrium, reversible coherent process, then

allows the excitation to "fly over" local energy traps generated by intrinsic static disorders of the protein matrix or simply explore alternative pathways.
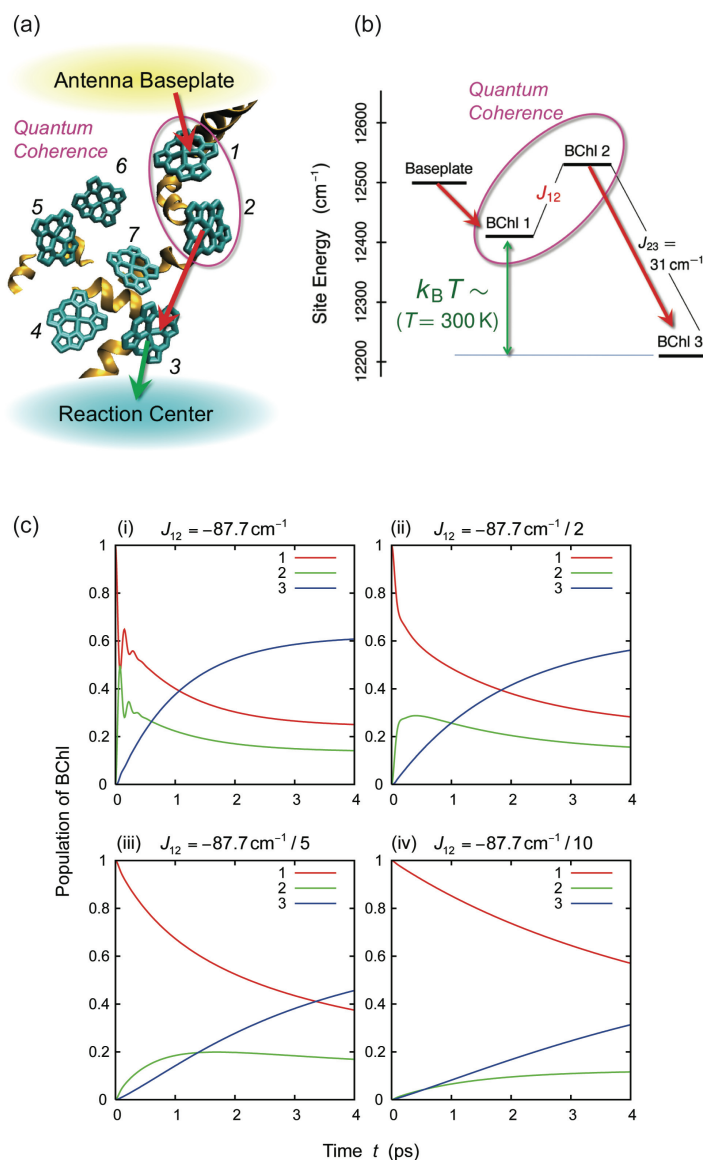

Fig.6. (a) One of the two primary transfer pathways in the FMO complex: baseplate → BChls 1 → 2 → 3. (b) The energy landscapes along the pathway. The relatively strong couplings between BChls are depicted by solid lines. (c) Population dynamics at different J_{13}. Reprinted by permission from National Academy of Sciences, USA. Originally published in Ref. [84].

A third application of coherence is less intuitively obvious. Coherence can be combined with the spatial and energetic layout of an energy transfer system to produce an "energy transfer rectifier" [84]. Consider the arrangement in Figure 6, which shows the energy and spatial layout of the FMO protein which acts as an energetic wire to connect the baseplate protein with the reaction center in green sulfur bacteria [94,95]. At first sight the arrangement seems very odd, because energy has to travel uphill to get from the input site (BChl 1) via BChl 2 to the output site (BChl 3). However BChls 1 and 2 are strongly coupled and form coherent excitonic states. By contrast the energy gap between BChls 2 and 3 is large and the coupling is weak, making the transfer from BChl 2

to BChl 3 incoherent. When the BChl 1-2 exciton is populated, amplitude from BChl 2 is irreversibly transferred to BCh 3. Reverse transfer from BChl 3 directly to BChl 1 is slow because the spatial separation is large. The overall setup makes the Boltzmann weights heavily in favor of BChl 3. Figure 6 shows how progressive increase of the coupling between BChls 1 and 3 increases the rate of BChl 1 to BChl 3 transfer.

A fourth potential application of coherence is the constructive or destructive interference of amplitude transferred along two (or more) distinct paths in an energy transfer network. This effect has been discussed by Silbey and coworkers [69]. As yet we are unaware of specific examples that have been suggested in light harvesting complexes.

Finally we turn to the interplay between the coherence and the fluctuations in the energy levels created by motions in the environment. Fluctuations between neighboring sites can be correlated, uncorrelated, or anticorrelated. Lee et al presented experiment evidence for strong positive correlation between two components of the bacterial reaction center [96]. Figure 7 shows the enhancement of energy transfer in a homo dimer in the correlated case. The right hand panel shows the enhanced coherence (delocalization) as quantified by a quantity known as concurrence. Concurrence is a measure of the bipartite entanglement, which in a single exciton system is equivalent to the coherence [97].
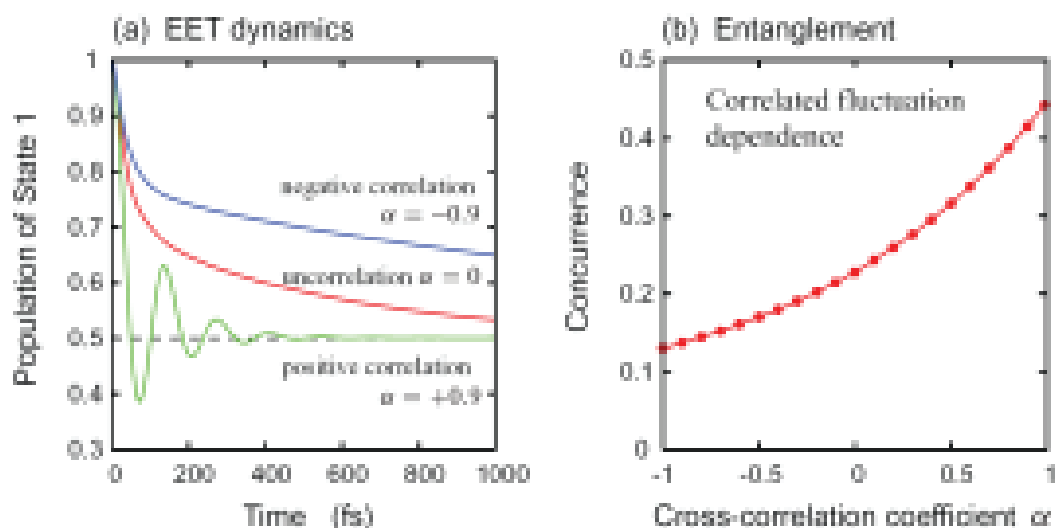

Fig.7. Impact of the correlated fluctuations in a homo-dimer upon (a) the electronic energy transfer dynamics and (b) the quantum entanglement in thermal equilibrium within the single-exciton manifold. Reprinted by permission from the Institute of Physics. Originally published in Ref. [85].

3.3. Can We Detect Interference Between Pathways?

Discussions on quantum effects in light harvesting often focus on long-lasting excitonic coherence and coherent wave-like dynamics. In our view, the central point should be the effects of quantum interference. The quintessential question of "to what extent are quantum mechanical effects involved in light harvesting?" should be posed with an emphasis on quantum interference. Coherence allows energy transfer pathways to interfere with each other and produce results that are not described by the classical probability laws. For example, quantum probability laws are formulated by summing amplitudes associated with each energy transfer pathway through a multichromophoric complex. The modulus of that quantity is squared to yield a probability versus time for the evolution of population densities, The cross-terms that arise naturally from this procedure (e.g. amplitude of pathway 1 multiplied by amplitude of pathway 2) correct the classical rate law for quantum-mechanical interferences. Experiments that probe quantum interference between explicit pathways will be critical for the understanding and control of quantum coherence effects in photosynthesis. For example, consider a system that exhibits two dominant pathways (e.g. the FMO complex). If the measurements of energy transfer efficiency on the conditions that either one of the two

pathway is blocked can be performed and compared to the results of the unmodified system, then we can truly bring to light the contributions of excitonic quantum coherence to the quantum efficiency of light harvesting.

The previous discussions about coherence are also highly relevant to the nature of pathways in the case of quantum tunneling of electrons in biological systems. Protein residues and solvent molecules (most likely water) provide low-lying virtual states that contribute to super-exchange electron transfer coupling between two distant sites. Multiple pathways for electron transfer could exist in the medium, and the effective coupling between the two sites depends on the interferences between all the pathways. If the pathways are random and the collective outcome of interferences is destructive, then dominant pathways do not exist and the details of the protein matrix is not important, which leads to the average-medium view of Dutton and coworkers [29,31]. On the other hand, if a few pathways dominate the electron tunneling reaction, then the interference between pathways plays a crucial role. Indeed, a detailed theoretical analysis of the azuin protein reveals distinct pathways across the protein and shows that the interference effects are important [22]. It is interesting to note that in a recent theoretical analysis, Beratan and coworkers [26] demonstrate that the two views of electron tunneling in proteins can be put in a unified description based on a simple criterion that depends on the dynamical fluctuations of the effective coupling. However, experimental evidence that can be used to distinguish the two limits by measuring interference effects is still lacking.

Recent advances in measuring coherent transport in single-molecule junctions may provide much useful insight to quantum tunneling in proteins [25, 98]. In particular, studies on bridged electron transfer across a small molecule with multiple pathways indicate that exciting bridge vibrations using infrared pulses can modulate electron transfer [99-102], effectively carrying out a electron which-way experiment in a molecular interferometer. Similar experiments on proteins or model systems with biological bridging residues should contribute significantly to elucidate the role of proteins in biological long-range electron tunneling reactions, and eventually shed light on whether or not evolution has taken advantage of such quantum control in the design of electron-transport proteins.

4. Developments Needed

4.1. Better understanding of the role of protein

A possible 'special' role played by the protein environment was first envisioned by Fröhlich [103,104]. The idea is that when heat is supplied to a bath of oscillators, it is predicted that a highly unusual distribution of excitations can result. An anomalous population distribution of excitation might be found for the lowest frequency modes. While this is a purely statistical mechanical process (not quantum), it has been likened to Bose-Einstein condensation. A number of researchers have examined Frölich's theory because it is thought that his 'condensation' might yield an ordering of fluctuations in a biological system that could, in turn, preserve coherences [105,106]. A recent report by Riemers and co-workers, however, concludes that unrealistic temperature conditions are required for the external heat bath in this model so it is unlikely to be of biological relevance [107].

Investigations of energy transfer have highlighted the critical role played by the environment. For example, the spectral overlap in Förster theory as well as the decoherence of quantum-coherent dynamics are caused by coupling of electronic transitions to the stochastic fluctuations of the environment. The frequency spectrum of the environment and how those frequencies couple to electronic transitions of the donor and acceptor (spectral density) is therefore an important quantity. In addition, experimental observations of long-lasting coherence in photosynthetic complexes indicate that nonlocal-bath effects can play a role in moderating the mechanism of excitation energy transfer [3,96,108]. To elucidate the effects of correlated baths on coherence dynamics, we need both theoretical and experimental studies of the electron-phonon interactions in realistic systems to reexamine the validity of linear system-bath couplings and uncorrelated baths. Finally, slow structural changes in the environment and molecular structure (slow compared to the excited state lifetime) influence energy transfer by contributing a static offset to transition energies in the ensemble. Such inhomogeneous line broadening can obscure observation of

dynamics at the level of individual proteins and effectively reduces delocalization of electronic excitation because it introduces transition energy differences between chromophores that, on average, are identical. Similarly the electronic coupling between chromophores can be subject to disorder originating from distributions of separation and orientation (off-diagonal disorder). A definitive experiment for discriminating diagonal and off-diagonal disorder has not yet been reported.

Equally important is the way the electronic coupling between molecules is influenced by the environment by dielectric screening. This more subtle off-diagonal effect is less studied and is usually lumped into a simplistic $1/n^4$ factor in Förster theory. Given that energy transfer rates are modified by a factor of ~4 by dielectric screening, it needs to be better understood. Quantum-chemical calculations have been shown to capture details of solvent screening of electronic couplings and the intrinsic distance-dependence of this screening [109] by assuming the dielectric environment is a polarizable continuum. However, the heterogeneity of a protein is well recognized, how that influences energy transfer by tuning the electronic coupling between molecules has yet to be ascertained.

The efficiency and rates for tunneling of electrons through proteins can be correlated to structure of the protein [23,24,31,110,111]. As a consequence, our understanding of how proteins influence electron tunneling is well established. A related area of interest is olfactory reception [112-114]. It has been realized that odorants are not discriminated solely by their shape and therefore how they bind to olfactory receptors. It has been suggested that a second ingredient acts together with the lock and key model, that is that the vibrational spectrum of the odorant is important. It has been suggested that the mechanism at play here is a phonon assisted tunneling of an electron between two receptor sites via the odorant. Here is an example where a more detailed understanding of the protein as well as its interactions with a bound analyte are critical for testing this hypothesis for the operation of olfactory receptors and the possible role of quantum-mechanical tunneling.

4.2. Accurate approximate, efficient theory for condensed-phase quantum dynamics

Because photosynthetic systems exhibit huge number of degrees of freedom and mixed strengths of interactions, a clear small parameter required by simple perturbative treatments is often not attainable. Accumulating experimental data have shown that our conventional views of excitation energy transfer based either on the Förster picture or the Redfield picture are inadequate for describing general coherent excitation energy transfer dynamics in photosynthetic complexes. In addition, issues such as the dynamics of coherence transfer, more general forms of system-bath couplings, how to treat high frequency vibrational modes, and dynamical localization effects are largely overlooked in present models of photosynthetic excitation energy transfer. A accurate and practical theoretical description of full coherent excitation energy transfer dynamics especially in the intermediate coupling regime is crucial for advancing our understanding of the true quantum effects in photosynthetic light harvesting.

Accurate and quantitative theoretical descriptions of quantum processes in the condensed phase remain a formidable challenge in theoretical chemistry. Although a rigorous formulation of the system-bath model leads to a generalized quantum master equation for the reduced-system density matrix that, in principle, describes the exact time-evolution of the system through a memory kernel function [115]. In practice, calculating the exact memory kernel is unfeasible and perturbation theory must be employed to obtain approximate results, which leads to, for example, the Förster theory or the Redfield theory. Numerically exact nonperturbative methods avoid this problem. However, they are often computationally expensive and only limited to a specific form of bath spectral density. These limitations hinder their ability to calculate dynamics in large pigment-protein complexes and to investigate system-bath correlations and environmental effects of photosynthetic light harvesting.

Therefore, the development of an accurate theory for photosynthetic excitation energy transfer that is numerically efficient and also applicable to a broad parameter regime will be crucial for the fundamental understanding of coherence quantum processes in photosynthesis. Such new theoretical developments should then be benchmarked against nonperturbative calculations before being used for quantitative study. We note that the huge literature concerning exciton and charge transport in organic molecular crystals that were developed in the '70s to the '80s

should provide a valuable reference point. Indeed, recently several research groups have applied the phenomenological Haken-Reineker-Ströbl model, which was originally developed for organic molecular crystals, to investigate geometry factors and the interplay of quantum coherent dynamics and dephasing in the efficiency of excitation energy trapping in photosynthetic complexes. Moreover, the small-polaron approach for coherent excitation energy transfer developed by Jang et al. also has its root in the Grover-Silbey theory for exciton transport in organic molecular crystals. Thus, a potentially fruitful venue for developing an accurate theory for excitation energy transfer in the intermediate coupling regime is to follow the variational polaron method developed by Yarkony and Silbey and later generalized by Cheng and Silbey. Professor Silbey will give a detailed review of these methods in his contribution to this conference. Note that these approaches can not be directly applied to photosynthetic excitation energy transfer, because in contrast to organic molecular crystals, photosynthetic complexes lack translational symmetry and also exhibit strong static disorder and a energetic landscape embedded in the site energies. All these additional complexities must be included in the theory in order to achieve an accurate description of light-harvesting excitation energy transfer.

4.3. Better Experimental Tools for Probing Quantum Coherence Dynamics

How do we quantify and interpret the contributions of quantum coherence to the efficiency of photosynthetic light-harvesting? The discovery of quantum beating signals in the FMO complex using 2DPE at 77K has motivated intensive theoretical and experimental works because it represents for the first time a method to explicitly probe the dynamics of coherence is available. More recently, Engel and coworkers demonstrated that with carefully designed algorithm, the beating signal can be used to quantitatively measure the beat frequencies and dephasing times of coherences [116]. Clearly, additional experimental tools that are sensitive to coherence dynamics of excitation energy transfer are required for us to go beyond population transfer and to probe the full quantum evolution of the entire density matrix that describes the excitations. In this section we discuss two extensions to photon-echo spectroscopy that should expand our toolbox for probing coherent dynamical phenomena in the condensed phase.
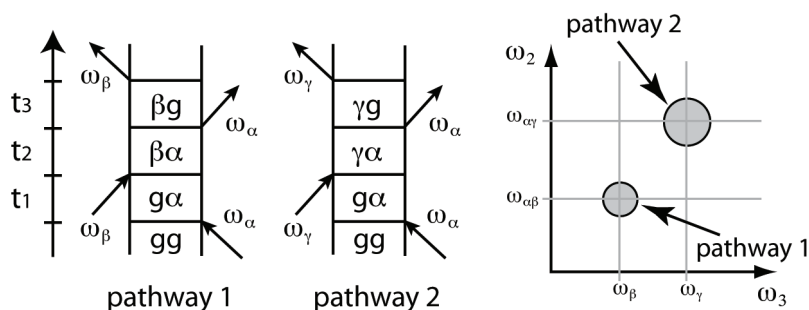

Fig.8. Quantum state tomography using element specific 2D electronic spectroscopy. In the experiment, the first two pulses (pump pulses) prepare the system in a 1-exciton superposition state, whose off-diagonal density matrix elements are the targets of the measurement. The third pulse (probe) interacts with the density matrix and stimulates the signal emission. For example, the double-sided Feynman diagrams describing two representative Liouville pathways are shown above (left), in which g denotes the ground state, Greek letters α, β, and γ denote different 1-exciton states, arrows represent interactions with laser pulses, and the laser-induced transitions of the density matrix elements are shown from bottom to top in the center. In pathway 1, the coherence $|\beta\rangle\langle\alpha|$ is prepared during the second delay (t_2), therefore, an oscillating phase factor with a frequency of $\omega_{\alpha\beta}=\omega_\alpha-\omega_\beta$ is associated with the signal as a function of t_2. The probe pulse then induces a signal at frequency ω_α. Therefore, after Fourier transforming the signals with respect to t_2, the pathway will generate a peak at (ω_α, $\omega_{\alpha\beta}$), as shown in the right panel. Similarly, pathway 2 will generate a 2D peak at (ω_γ, $\omega_{\alpha\gamma}$). The amplitudes of these peaks are determined by the density matrix elements, the strengths of system-field interactions, and the correlations between exciton states. Experimental and theoretical tools can be developed to account for the contributions from the last two factors. As a result, the element specific 2D spectroscopy can provide a 2D spectrum that correlates the density matrix elements prepared by the first two pulses and the emitting signal frequencies, enabling the detection of specific density matrix elements. Reprinted by permission of the Institute of Physics and Deutsche Physikalische Gesellschaft. Originally published in Ref.[85].

The conventional 2DPE scheme can be modified to create a new 2D technique that is specifically sensitive to the off-diagonal density matrix elements of the system prepared by the first two pulses, thus allowing the characterization of the full density matrix (quantum state tomography). In this element-specific 2D electronic spectroscopy (Fig. 8), the first time delay t_1 is set to zero (or other fixed time interval) and the second time delay t_2 is scanned to enable the Fourier transform of the signal field with respect to t_2. The resulting 2D spectrum as a function of ω_2 and ω_3, which are conjugated variables of t_2 and t_3, respectively, provides a map of correlation peaks between the characteristic frequency of the density matrix elements of the 1-exciton superposition state (ω_2) and the frequency of the emitted signal (ω_3). In Figure 8 we show two representative Liouville pathways that contribute to the 2D signals and a schematic of an element specific 2D spectrum. This technique specifically probe signals generated from systems prepared in a 1-exciton superposition state during t_2, and each peak in the spectrum can be assigned to a specific pathway, i.e. a specific density matrix element. Therefore, by combining knowledge of the transition dipole moment strengths and correlations between exciton states, the amplitude of a peak can be used to determine the corresponding coherence matrix element of the density matrix of the system prepared by the first two pulses. Because in this scheme, contributions from different density matrix elements can be identified separately to enable the characterization of multiple density matrix elements in a single experiment, this form of 2D spectroscopy can become a valuable tool for quantum state tomography.

Following the measurement of the full density matrix of an excitonic system, we turn to describe a proposal that potentially can be used to detect dynamics involving transfers between coherence density matrix elements or between a population and a coherence. Such coherence transfer dynamics are generally overlooked in previous studies of photosynthetic excitation energy transfer. However, recent 2DPE experiments suggest that coherence transfer is an important process that should be included in a complete model for dynamics of quantum multilevel systems in photosynthesis. To directly monitor coherence transfer processes, the following spectrally resolved two-color three pulse photon-echo experiment can be useful: Consider a two-color three-pulse photon-echo setup where the first two pulses are set to a "pump" wavelength and the third pulse is set to a distinct "probe" wavelength. Without coherence transfer processes, the stimulated signal observed at the phase-matching condition $k_s = k_3 + k_2 - k_1$ will contain only peaks at the probe wavelength. However, if coherence transfer occurs, a pathway that results in an emission at the pump wavelength becomes possible, as the example shown in Fig. 9. Therefore, the observation of photon-echo peaks at the pump wavelength in the spectrally resolved two-color experiment will directly provide information on the coherence transfer dynamics, and the intensity evolution as a function of the delay time could be used to quantify the dynamics of coherence transfer.
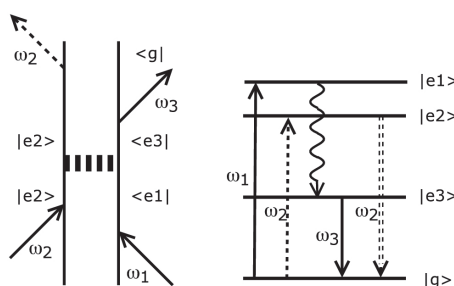

Fig.9. The Feynman diagram (left) and level diagram (right) representation of a coherence transfer pathway that results in the photon-echo signal at the pump wavelength. In the level diagram, the solid (dashed) arrow represents an interaction of electric field with a bra-(ket-) state, and the wiggling arrow represents the coherence transfer. $\left| g \right\rangle$ is the ground state, and $\left| e_1 \right\rangle$, $\left| e_2 \right\rangle$, and $\left| e_3 \right\rangle$ are electronically excited states. Excited states $\left| e_1 \right\rangle$ and $\left| e_2 \right\rangle$ absorb photons at the pump wavelength, while another excited state $\left| e_3 \right\rangle$ absorbs at a distinct wavelength. Without coherence transfer, the third pulse can only interact resonantly with a ket-state, which always results in a photon-echo signal at ω_3.

We discussed in this section two proposals for achieving a specific and quantitative experimental tool to probe coherence dynamics beyond the conventional picture of quantify energy transfer using a population distribution and population transfer dynamics. Expanding our models for excitation energy transfer to include the complete scope of

dynamical processes involving coherence density matrix elements is essential to the full understanding of the quantum aspects of photosynthesis. Clearly, many more methods can be developed to achieve this goal. We emphasize that energy transfer in photosynthetic systems often occurs on a sub-picosecond time scale and requires ultrafast temporal resolution for the acquisition of information on dynamical processes. This prerequisite together with the condition that light-harvesting is initiated by absorption of photons have made ultrafast spectroscopic methods indispensable tools for probing EET dynamics in photosynthesis. Continuous progresses in the area of emerging nonlinear optical spectroscopic techniques should provide deeper insight into the interactions and coherent quantum dynamics of photosynthetic complexes.

4.4. Evidence for biological relevance

Quantum biology is a concept that has been discussed fairly widely for many years, however it can still be argued that there is no unequivocal example of a quantum mechanical process playing an important role in biology where a classical process could otherwise suffice. That is not to say that there is no evidence for quantum mechanical processes playing roles in biology—as we have discussed in this article there is evidence, particularly that photosynthetic proteins use quantum-mechanical mechanisms. In recent work, as already discussed, evidence for manifestly quantum effects involved in the operation of isolated photosynthetic light-harvesting proteins from green sulfur bacteria, purple bacteria, cryptophyte algae, and higher plant antenna systems have been identified. When these proteins operate *in vivo*, where they are not isolated, is the importance of quantum mechanical energy transfer mechanisms lessened? What approaches can be used to assess the biological relevance or necessity of those quantum-mechanical phenomena? Biological significance is not easy to quantify directly. For example, quantum-coherent light-harvesting does not necessarily translate into increased photosynthetic activity because other processes (e.g. CO_2 fixation) can be limiting under various environmental conditions.

One way to answer the question of biological relevance would be to argue that the process would simply not work without quantum mechanics. Vision is one such example because the quantum mechanical arrangement of electronic states and their symmetries is responsible for light-activated isomerization. Such photochemical reactions are a subset of chemical reactions in general, and the mechanism of many ground state reactions can also only be understood from a quantum-mechanical basis. Another example is the radical mechanism for magnetoreception because its role is clearly proven in whole organism behavioral experiments. In this instance the mechanism must first be proven to be responsible for magnetoreception. Tunneling processes through proteins are clearly mechanistically significant in redox process, for example those occurring in respiratory chains. We could ask why tunneling is needed to perform these tasks?

Another approach is to ask whether or not biological systems recognize quantum-mechanical mechanisms as a trait that confers fitness. In other words, it would be compelling to discover whether quantum-mechanical aspects of processes like light-harvesting have been fine tuned during evolution. The traits of living organisms, their relationships, and their evolution from one species to another are described by phylogenetic reconstruction. Phylogenetic analysis has played an important role in establishing relationships among species of organisms and between phyla. Perhaps similar analyses can be used to examine biophysical traits and establish how photophysical and molecular-level mechanisms have evolved or have contributed to species diversification? For example, GDS and co-workers are mapping results of spectroscopic experiments and theoretical analyses onto an evolutionary tree already determined from phylogenetic analysis of cryptophyte lineages. Our goal is to establish whether the quantum-mechanical phenomena contributing to cryptophyte light-harvesting are selected for.

Acknowledgements

References

[1] E. Schrödinger, What Is Life?, Cambridge University Press, Cambridge, 1944.
[2] A.S. Davydov, Biology and Quantum Mechanics, Pergamon Press, New York, 1982.
[3] G.S. Engel, T.R. Calhoun, E.L. Read, T.-K. Ahn, T. Mancal, Y.-C. Cheng, R.E. Blankenship, G.R. Fleming, Nature, 446 (2007) 782.
[4] M. Sarovar, A. Ishizaki, G.R. Fleming, K.B. Whaley, Nature Physics, 5 (2010) 1.
[5] A.W. Chin, A. Datta, F. Caruso, S.F. Huelga, M.B. Plenio, New J. Phys., 12 (2010) 065002.
[6] M.B. Plenio, S.F. Huelga, New J. Phys., 10 (2008) 113019.
[7] P. Rebentrost, M. Mohseni, A. Aspuru-Guzik, J. Phys. Chem. B, 113 (2009) 9942.
[8] M. Mohseni, P. Rebentrost, S. Lloyd, A. Aspuru-Guzik, J. Chem. Phys., 129 (2008) 174106.
[9] E. Collini, C.Y. Wong, K.E. Wilk, P.M.G. Curmi, P. Brumer, G.D. Scholes, Nature, 463 (2010) 644.
[10] G. Panitchayangkoon, D. Hayes, K.A. Fransted, J.R. Caram, E. Harel, J. Wen, R.E. Blankenship, G.S. Engel, Proc. Natl. Acad. Sci. USA, 107 (2010) 12766.
[11] S.R. Hameroff, Philos. Trans. Roy. Soc. A, 356 (1998) 1869.
[12] S.R. Hameroff, Anesthesiology, 105 (2006) 400.
[13] P. Davies, Biosystems, 78 (2004) 69.
[14] P. Schuster, Complexity, 15 (2009) 8.
[15] H.C. Longuet-Higgins, Biophys. J., 2 (1962) 207-215.
[16] H. van Amerongen, L. Valkunas, R. van Grondelle, Photosynthetic Excitons, World Scientific Publishing Company, 2000.
[17] R.E. Blankenship, Molecular Mechanisms of Photosynthesis, Wiley-Blackwell;, 2002.
[18] D. DeVault, B. Chance, Biophys. J., 6 (1966) 825.
[19] R. Marcus, N. Sutin, Biochim. Biophys. Acta, 811 (1985) 265.
[20] H.B. Gray, J.R. Winkler, Q. Rev. Biophys., 36 (2003) 341.
[21] H.B. Gray, J.R. Winkler, Proc. Natl. Acad. Sci. USA, 102 (2005) 3534.
[22] J. Regan, J.N. Onuchic, Adv. Chem. Phys., 107 (1999) 497.
[23] D.N. Beratan, J.N. Onuchic, J.R. Winkler, H.B. Gray, Science, 258 (1992) 1740.
[24] J.N. Onuchic, D.N. Beratan, J.R. Winkler, H.B. Gray, Annu. Rev. Bioph. Biom., 21 (1992) 349.
[25] S.S. Skourtis, D.H. Waldeck, D.N. Beratan, Annu. Rev. Phys. Chem., 61 (2010) 461.
[26] T.R. Prytkova, I.V. Kurnikov, D.N. Beratan, Science, 315 (2007) 622.
[27] A. Stuchebrukhov, Theor. Chem. Acc., 110 (2003) 291.
[28] S.S. Skourtis, D.N. Beratan, Adv. Chem. Phys., 106 (1999) 377.
[29] C.C. Moser, J.L.R. Anderson, P.L. Dutton, BBA-Bioenergetics, 1797 (2010) 1573.
[30] C. Page, C. Moser, P. Dutton, Curr. Opin. Chem. Biol., 7 (2003) 551.
[31] C. Page, C. Moser, X. Chen, P. Dutton, Nature, 402 (1999) 47.
[32] J. Regan, A. Dibilio, R. Langen, L. Skov, J.R. Winkler, H.B. Gray, J.N. Onuchic, Chem Biol, 2 (1995) 489.
[33] J. Regan, S. Risser, D.N. Beratan, J.N. Onuchic, J. Phys. Chem., 97 (1993) 13083.
[34] R.K. Allemann, N.S. Scrutton, Quantum Tunnelling in Enzyme-Catalysed Reactions, RSC Publishing, Cambridge, UK, 2009.
[35] M.H.V. Huynh, T.J. Meyer, Chem. Rev., 107 (2007) 5004.
[36] S.Y. Reece, D.G. Nocera, Annu. Rev. Biochem., 78 (2009) 673.
[37] Z.D. Nagel, J.P. Klinman, Chem. Rev., 106 (2006) 3095.
[38] A. Sen, A. Kohen, J. Phys. Org. Chem., 23 (2010) 613.
[39] Y. Cha, C. Murray, J. Klinman, Science, 243 (1989) 1325.
[40] A. Kohen, Prog. React. Kinet. Mec., 28 (2003) 119.
[41] A. Kohen, R. Cannio, S. Bartolucci, J.P. Klinman, Nature, 399 (1999) 496.
[42] J. Nesheim, J. Lipscomb, Biochemistry, 35 (1996) 10240.
[43] K. Rickert, J. Klinman, Biochemistry, 38 (1999) 12218.
[44] J.N. Bandaria, C.M. Cheatum, A. Kohen, J. Am. Chem. Soc., 131 (2009) 10151.
[45] R.A. Marcus, J. Chem. Phys., 125 (2006) 194504.
[46] R.A. Marcus, J. Phys. Chem. B, 111 (2007) 6643.
[47] S. Hammes-Schiffer, A.V. Soudackov, J. Phys. Chem. B, 112 (2008) 14108.
[48] J.P. Bothma, J.B. Gilmore, R.H. McKenzie, New J. Phys., 12 (2010) 055002.
[49] S.C.L. Kamerlin, A. Warshel, J. Phys. Org. Chem., 23 (2010) 677.
[50] R. Wiltschko, W. Wiltschko, Magnetic orientation in animals, Springer, Berlin, 1995.
[51] J. Kirschvink, M. Walker, C. Diebel, Curr. Opinion Neurobiol. 11 (2001) 462.
[52] C.T. Rodgers, P.J. Hore, Proc. Natl. Acad. Sci. USA, 106 (2009) 353.
[53] E. Wajnberg, D. Acosta-Avalos, O.C. Alves, J.F. de Oliveira, R.B. Srygley, D.M.S. Esquivel, J. R. Soc. Interface, 7 (2010) S207.
[54] C. Mora, M. Davison, J. Wild, M. Walker, Nature, 432 (2004) 508.
[55] C. Diebel, R. Proksch, C. Green, P. Neilson, M. Walker, Nature, 406 (2000) 299.
[56] M. Walker, T. Dennis, J. Kirschvink, Current opinion in neurobiology, 12 (2002) 735.
[57] W. Wiltschko, R. Wiltschko, Science, 176 (1972) 62.

[58] J. Kirschvink, J. Gould, Biosystems, 13 (1981) 181.
[59] M. Winklhofer, J.L. Kirschvink, J. R. Soc. Interface, 7 (2010) S273.
[60] J.L. Kirschvink, M. Winklhofer, M.M. Walker, J. R. Soc. Interface, 7 (2010) S179.
[61] W. Wiltschko, U. Munro, H. Ford, R. Wiltschko, Nature, 364 (1993) 525.
[62] M. Leask, Nature, 267 (1977) 144.
[63] T. Biskup, E. Schleicher, A. Okafuji, G. Link, K. Hitomi, E.D. Getzoff, S. Weber, Angew. Chem. Int. Edit., 48 (2009) 404.
[64] T. Ritz, P. Thalau, J. Phillips, R. Wiltschko, W. Wiltschko, Nature, 429 (2004) 177.
[65] B. Brocklehurst, Chemical Society Reviews, 31 (2002) 301.
[66] T. Ritz, M. Ahmad, H. Mouritsen, R. Wiltschko, W. Wiltschko, J. R. Soc. Interface, 7 (2010) S135.
[67] W. Wiltschko, M. Gesson, R. Wiltschko, Naturwissenschaften, 88 (2001) 387.
[68] W. Wiltschko, M. Gesson, K. Stapput, R. Wiltschko, Naturwissenschaften, 91 (2004) 130.
[69] J. Cao, R.J. Silbey, J. Phys. Chem. A, 113 (2009) 13825.
[70] A. Olaya-Castro, C.F. Lee, F.F. Olsen, N.F. Johnson, Phys. Rev. B, 78 (2008) 7.
[71] H. Sumi, Chem. Rec., 1 (2002) 480.
[72] H. Sumi, J. Phys. Chem. B, 103 (1999) 252.
[73] G.D. Scholes, G.R. Fleming, J. Phys. Chem. B, 104 (2000) 1854.
[74] G. Scholes, X. Jordanides, G.R. Fleming, J. Phys. Chem. B, 105 (2001) 1640.
[75] S. Jang, M.D. Newton, R.J. Silbey, Phys. Rev. Lett., 92 (2004) 218301.
[76] Y.-C. Cheng, G.R. Fleming, Annu. Rev. Phys. Chem., 60 (2009) 241.
[77] D. Beljonne, C. Curutchet, G.D. Scholes, R.J. Silbey, J. Phys. Chem. B, 113 (2009) 6583.
[78] V.I. Novoderezhkin, R. van Grondelle, Phys. Chem. Chem. Phys., 12 (2010) 7352.
[79] S. Jang, J. Chem. Phys., 131 (2009) 164101.
[80] S. Jang, Y.-C. Cheng, D.R. Reichman, J.D. Eaves, J. Chem. Phys., 129 (2008) 101104.
[81] A. Ishizaki, G.R. Fleming, J. Chem. Phys., 130 (2009) 234110.
[82] A. Ishizaki, G.R. Fleming, J. Chem. Phys., 130 (2009) 234111.
[83] A. Ishizaki, T.R. Calhoun, G.S. Schlau-Cohen, G.R. Fleming, Phys. Chem. Chem. Phys., 12 (2010) 7319.
[84] A. Ishizaki, G.R. Fleming, Proc. Natl. Acad. Sci. USA, 106 (2009) 17255.
[85] A. Ishizaki, G.R. Fleming, New J. Phys., 12 (2010) 055004.
[86] F. Fassioli, A. Olaya-Castro, New J. Phys., 12 (2010) 085006.
[87] F. Caruso, A.W. Chin, A. Datta, S.F. Huelga, M.B. Plenio, Phys. Rev. A, 81 (2010) 062346.
[88] N. Makri, D.E. Makarov, J. Chem. Phys., 102 (1995) 4600.
[89] N. Makri, D.E. Makarov, J. Chem. Phys., 102 (1995) 4611.
[90] F. Nesi, E. Paladino, M. Thorwart, M. Grifoni, Phys. Rev. B, 76 (2007) 155323.
[91] B.J. Berne, G. Cicotti , D.F. Coker, Classical and Quantum Dynamics in Condensed Phase Simulations, World Scientific, Singapore, 1998.
[92] G. Tao, W.H. Miller, J. Phys. Chem. Lett., 1 (2010) 891.
[93] P. Nalbach, J. Eckel, M. Thorwart, New J. Phys., 12 (2010) 065043.
[94] J.M. Olson, Photosyn. Res., 80 (2004) 181.
[95] A. Camara-Artigas, R.E. Blankenship, J.P. Allen, Photosyn. Res., 75 (2003) 49.
[96] H. Lee, Y.-C. Cheng, G.R. Fleming, Science, 316 (2007) 1462.
[97] S. Hill, W. Wootters, Phys. Rev. Lett, 78 (1997) 5022.
[98] D.N. Beratan, S.S. Skourtis, I.A. Balabin, A. Balaeff, S. Keinan, R. Venkatramani, D. Xiao, Acc. Chem. Res., 42 (2009) 1669.
[99] A. Troisi, J.M. Beebe, L.B. Picraux, R.D. van Zee, D.R. Stewart, M.A. Ratner, J.G. Kushmerick, Proc. Natl. Acad. Sci. USA, 104 (2007) 14255.
[100] M. Galperin, M.A. Ratner, A. Nitzan, J. Phys.-Condens. Mat, 19 (2007) 103201.
[101] Z. Lin, C.M. Lawrence, D. Xiao, V.V. Kireev, S.S. Skourtis, J.L. Sessler, D.N. Beratan, I.V. Rubtsov, J. Am. Chem. Soc., 131 (2009) 18060.
[102] D. Xiao, S.S. Skourtis, I.V. Rubtsov, D.N. Beratan, Nano Lett., 9 (2009) 1818.
[103] H. Frohlich, Int. J. Quantum Chem., 2 (1968) 641.
[104] H. Frohlich, Int. J. Quantum Chem., 23 (1983) 1589.
[105] T. Wu, Bioelectrochemistry and Bioenergetics, 41 (1996) 19.
[106] M. Mesquita, A. Vasconcellos, R. Luzzi, Int. J. Quantum Chem., 60 (1996) 689.
[107] J.R. Reimers, L.K. McKemmish, R.H. Mckenzie, A.E. Mark, N.S. Hush, Proc. Natl. Acad. Sci. USA, 106 (2009) 4219.
[108] T.R. Calhoun, N.S. Ginsberg, G.S. Schlau-Cohen, Y.-C. Cheng, M. Ballottari, R. Bassi, G.R. Fleming, J. Phys. Chem. B, 113 (2009) 16291.
[109] G.D. Scholes, C. Curutchet, B. Mennucci, R. Cammi, J. Tomasi, J. Phys. Chem. B, 111 (2007) 6978.
[110] C. Moser, J. KESKE, K. Warncke, R. FARID, P. Dutton, Nature, 355 (1992) 796.
[111] S.L. Mayo, W. Ellis, R. Crutchley, H.B. Gray, Science, 233 (1986) 948.
[112] L. Turin, Chemical Senses, 21 (1996) 773.
[113] J.C. Brookes, F. Hartoutsiou, A.P. Horsfield, A.M. Stoneham, Phys. Rev. Lett., 98 (2007) 038101.
[114] J.C. Brookes, Philos. Trans. Roy. Soc. A, 368 (2010) 3491.
[115] R. Zwanzig, Nonequilibrium Statistical Mechanics, Oxford University Press, Oxford, 2001.
[116] D. Hayes, G. Panitchayangkoon, K.A. Fransted, J.R. Caram, J. Wen, K.F. Freed, G.S. Engel, New J. Phys., 12 (2010) 065042.