scale of a few micrometres over which the neutrons' vertical wavefunction extends and the potential sub-peV energy sensitivity of this spectroscopy may enable a class of tests of Newtonian gravity and prove useful in the search for short-range forces. There is now an active programme aimed at refining and applying this technique, and we can look forward to future results.

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QUANTUM BIOLOGY

Coherence in photosynthesis

Evidence is growing that quantum coherence plays a role in photosynthesis. Better understanding of this process might help us design more efficient solar cells to harness the Sun's energy.

Gregory D. Scholes

Discovering new ways to produce energy is a crucial challenge for this century. Photosynthesis is currently the largest energy-conversion process on Earth. Some aspects of how photosynthesis works — especially the light-initiated reactions — can inspire technologies that include solar fuel production and sensors. Evidence that proteins involved in the photosynthetic machinery are capable of supporting quantum-coherent energy transport at normal temperatures has generated controversy over its implications for biology and synthetic materials that interconvert energy and light. This subject and its significance were discussed at The Royal Society Theo Murphy International Scientific Meeting on 'Quantum-Coherent Energy Transfer: Implications for Biology and New Energy Technologies', 27–28 April 2011. The organizers, Alexandra Olaya-Castro (University College London), Ahsan Nazir (Imperial College London) and Graham Fleming (University of California, Berkeley), provided a lively forum for discussion of the relevant issues, challenges and misconceptions.

The operation of the natural photosynthetic apparatus has long fascinated researchers owing to its precision, complexity and the physical principles underlying its function. Various protein units perform specialized tasks such as light harvesting, short- and long-range charge separation, extraction of electrons from water and so on. Robust feedback and control loops regulate the interplay of these processes as a function of incident-light conditions and nutrient supplies. In comparison, man-made solar fuel production so far relies on large material domains that serve as 'jacks of all trades' — both harvesting solar energy and

transporting charge carriers. A reason for this is that, although remarkable chemical architectures can be synthesized, their assembly into macroscopic structures is poorly controlled, or at least imprecise. Nonetheless, natural and synthetic systems address similar challenges. Notably, the dissociation of electronic excited states into mobile charges requires an energetically costly driving force.

Future energy technologies are foreseen to include new synthetic structures, new paradigms in the control of electronic states, and the ability to selectively harness the machinery provided by nature. How these advances might come about was discussed by the multidisciplinary participants of the meeting, whose expertise spanned biological, chemical, engineering and quantum sciences. Processes on timescales from femtoseconds to millions of years were described. Many presentations focused on the question 'how do quantum-coherent effects help?'.

Decades ago, careful measurements of the electronic absorption spectra of molecular crystals revealed how electronic transitions are often split into two bands as a result of quantum-mechanical sharing of the energy absorbed from light — this Davydov splitting indicates molecular exciton states. However, because such effects are overwhelmed by broad absorption lineshapes in most chemical and biological systems, it was concluded that such quantum sharing of electronic excitation by two or more molecules would be rapidly lost (dephased or decohered). Hence quantum mechanics could not be harnessed to help move electronic excitation through multimolecular arrays such as photosynthetic light-harvesting complexes.

Experiments based on two-dimensional optical spectroscopy using sequences of femtosecond laser pulse, have now been used by researchers in Berkeley, Chicago and Toronto to re-examine this issue. It was found that excitonic phase relationships (quantum coherence) are preserved for quite some time after the photoexcitation of photosynthetic proteins and conjugated polymers like those used in organic solar cells. This work has inspired theory groups to work out what the implications of quantum coherence will be. A challenging problem indeed because the dynamics of the electronic system, that is the sharing and transfer of photoexcitation, occurs on similar timescales to those interactions with the environment that erase quantum phase information. One conclusion of the conference is that this confluence of timescales in optimized light-harvesting systems is probably not a coincidence.

Questions raised at the conference will inspire future research. For example, it is speculated that quantum coherence can optimize functions including robustness against disorder or perturbations and energy-transfer 'ratchets' caused by the interplay of coherence and decoherence. But we do not know if photosynthetic light harvesting is, or needs to be, optimized to make use of coherence. Moreover, are there other roles that could be played by quantum effects in sensing, regulation or photoprotection? Can quantum coherence be helpful in the rugged energy landscape of an organic polymer film for exciton diffusion? Can it help charge separation in organic photovoltaics? How can coherent effects found in some supramolecular structures be beneficial on the longer length-scales of assembled systems? Can quantum effects in crowded molecular systems be used as a quantum resource?

The next step seems to be elucidating how we can write a blueprint to 'make something' based on what we have learned from photosynthetic complexes and multichromophoric synthetic systems. To do this we need to address a number of outstanding issues. These include working out how to increase the length scale over which quantum effects influence dynamics. At present this issue is challenged by the complexity of information obtained by experimental studies of large systems. Similarly, there are challenges for theory, though not only in regards to treating large systems. We may also need to consider more carefully the molecules that comprise the electronic system. Given their intrinsic complexity compared with notional 'two-level systems', we should give some thought to what attributes those components contribute to the system. Similarly, realizing the importance of the environment, we should elucidate design principles for the structural scaffold or matrix. To aid advances in this direction, we need experiments to probe the relevant environmental response more directly. The meeting showed that theoretical models for energy transfer are converging, but there remain opportunities for theories that make predictions that change how we think about energy-transfer dynamics. Especially for synthetic solar fuel production or more speculative technologies, it is desirable to harness quantum coherence to help more than light harvesting — for example, to aid the interplay between energy transfer and charge separation. Interestingly, photosystem II, the enzyme responsible for photosynthetic oxygen production, may provide clues for this challenge.

Clearly this is a rich field. Incisive experiments have reinvigorated energy-transfer research. The resulting accelerated development of theories has been breathtaking. The stage is set for young researchers to solve the new challenges now in sight. ❐

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BUBBLE NUCLEATION

Stout fizz-ics

It has long been known that nucleation sites are essential to give carbonated drinks their fizz. Spontaneous bubble formation at a smooth surface only occurs in liquids that are supersaturated with dissolved gas. Without nucleation, a glass of champagne would seem lifeless and still, and a pint of lager poured from a can or bottle wouldn't form much of a head. In practice this isn't a problem, as preparing a glass that it is free from the impurities that generate bubbles — such as cellulose fibres from the environment — is actually quite difficult.

But for stout beer, which is infused with a mixture of carbon dioxide and nitrogen gas, this isn't enough. To try to figure out why, William Lee and colleagues have extended a mathematical model that successfully describes the formation of bubbles in a purely carbonated liquid to one that describes a liquid containing a mixture of dissolved gases (W. T. Lee *et al.*, http://arxiv.org/abs/1103.0508; 2011).

There are many reasons for using nitrogen in place of some of the carbon dioxide in stout. The lower concentration of carbon dioxide lowers the beer's acidity. And bubbles of nitrogen tend to be smaller and more numerous than those of carbon dioxide, giving stout its characteristic

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creamy texture. This doesn't present any problems for draught stout served in a pub, which is forced through a perforated metal plate that agitates the beer to produce the requisite bubbles.

But when delivered from a can or bottle, the agitation is much less vigorous, producing fewer bubbles and a less fulsome head. To compensate for this, many canned stouts use a hollow ball — commonly referred to as a widget — containing pressurized nitrogen that rushes out when that can is opened, to break up into hundreds of millions of tiny bubbles in the resulting turbulent flow.

Lee and colleagues wondered whether nitrogen bubbles simply don't nucleate by the same process that carbon dioxide bubbles do, and whether it might be possible to promote their formation by some other mechanism. The model they subsequently developed suggests that nitrogen bubbles can in fact form by nucleation, but they do so at a rate that is much slower than carbon dioxide.

As a test, they immersed a cellulose fibre drawn from a coffee filter in a glass of canned stout and observed it under a microscope. They found that bubbles did indeed grow slowly, but regularly, from the fibre. This prompted them to speculate that coating the inside of a can with such fibres might produce enough bubbles quickly enough to remove the need for pressurized widgets. But whether that is economically viable, they leave for a more sober head to decide.

ED GERSTNER