Entanglement in Biology

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Abstract: Already in early times of quantum theory, its possible role within biology was discussed. In recent years, significant progress has been made with experiments on entanglement. It was found (among other results) that the conditions for entanglement to arise can be loosened, its observation becomes easier and more accurate, and its chances to persist under adverse conditions gradually improve. Particularly it was detected that entanglement can occur and persist under higher temperatures than supposed before.
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1 Early Contacts between Quantum Theory and Biology

Already in the early times of quantum theory, when it still was far from being generally accepted, the idea that this theory might have some relevance for biology was formulated by some of its pioneers, such as Niels Bohr, Wolfgang Pauli, and Erwin Schrödinger (see, e.g., Bohr (1960), van Speybroeck (2009), Schrödinger (1935, 1944)). But in practice, these ideas did not play a significant role within biology for many years. Some biologists even claimed that quantum effects are excluded in biology for principal reasons (Bünning 1943).

A new perspective came in when a couple of years ago marked progress has been made in the study of an essential quantum phenomenon: entanglement. In a variety of experiments it has been found that the conditions for entanglement to arise can be loosened, its observation becomes easier and more accurate, and its chances to persist under adverse conditions gradually improve. It is the aim of this paper to summarize experiments of this kind and to discuss their possible implications for biology.

2 Basic Facts about Nonlocality and Entanglement

Nonlocality and entanglement belong to the foremost discoveries of modern quantum theory. After the experiments by Aspect et al. (1982a, b), these theoretical concept can be regarded as definitively confirmed. Nonlocal correlations over more than 10 km were demonstrated by Tittel et al. (1998a, b); more recently, in an experiment by Anton Zeilinger and his team photons remained entangled over a distance of 144 km (Perdigues Armengol et al. 2008). The observed correlations between measurements performed on spatially separated objects cannot be explained by any theory which is constrained to local variables. "Spatially separated" means that, within a given time limit, one object cannot reach another object by signalling, taking into account the velocity of light as the ultimate bound. These experiments cannot be interpreted as causal interaction; nor can nonlocality be used for "superluminal communication".

Entanglement is an exclusively quantum property having no classical counterpart. From a phenomenological perspective, entanglement can be understood as a concrete, observable correlatedness between two or more spatially separated entities. The term "entities" has been deliberately chosen: it will be shortly seen that we need a comprehensive term. Recent experiments show that entanglement is not only a matter of a few particles or waves – rather, two "entire beams of light" (Boyer et al. 2008), two laser beams (Wagner et al. 2008), or two separate samples of atoms containing 10^{12} atoms each (Julsgaard et al. 2001) can be entangled. The generic term "entities" includes as well objects and processes. Furthermore, entanglement can have an influence on macroscopic quantities, like heat capacity or magnetic properties (Vedral 2003).

3 Modern Experiments on Entanglement

There is quite a variety of experimental results which may suggest that, in the near future of biology, there will be an increasing interest in entanglement, when conditions for entanglement to occur and to persevere will become less restrictive, and techniques of observation will advance:

1. Entanglement is no more an exclusive matter of microphysics. "Now, however, entanglement is recognized to be ubiquitous and robust." (Vedral 2008: 1004) There is work in progress on "entanglement in macroscopic systems" (Müller-Ebhardt et al. 2008).
2. In special laboratory settings, entanglement can be possible at high temperatures, or persist in spite of increasing temperature (Ferreira et al. 2006, Amico et al. 2008, Briegel and Popescu 2008, Markham et al. 2008); it can occur "even at room temperature, without the need for any manipulation" (Vedral 2008: 1006).
3. Again in special settings, some systems properties due to entanglement are accessible to external macroscopic observation (Kofler and Brukner 2006, Vedral 2008).
4. Entanglement between two photons can even persist in spite of massive obstacles placed in their paths. Altewischer et al. (2002) placed optically thick metal films perforated with a periodic array of subwavelength holes in the path of two entangled photons. It was found that the photons were converted into surface-plasmon waves, which tunnel through the holes before reradiating as photons at the far side, and entanglement survives this conversion process.
5. Multi-particle entanglement: Chances are growing to entangle more then just two or three entities (Eisert and Gross 2006); entanglement of two separated mechanical oscillators has been demonstrated (Jost et al. 2009)

Entanglement is the basis of the 'avian compass', the ability of certain migratory birds to sense very subtle variations of Earth's magnetic field. Pairs of spatially separated, but entangled electrons are influenced by external magnetic fields, and by specific mechanisms, meanwhile well explored, this effect is registered and further processed (Gauger et al. 2009).

4 The Enigmatic Stability of Biological Systems

4.1 Decoherence and the Helicobacter Fallacy

In its original and general meaning *decoherence* denotes the decay of a wave process (a single wave or an ordered ensemble) due to uncontrolled interaction with the environment. In the context of entanglement, decoherence takes on a special role. Entanglement is always endangered: it is at risk of being degraded or finally extinguished by the unavoidable interaction between the system and its environment (see, e.g., Duplantier et al. (2006), Schlosshauer (2007)). This is of enormous practical importance, because quantum computation and communication depend on the longevity of entanglement in multi-particle systems. The decoherence rate depends on the temperature of the environment and on the strength of the coupling with the environment.

But before entering a discussion about entanglement in biology and its chance to assert itself against its primary opponent, decoherence, we should have a look on a characteristic pattern of misjudgement and fallacy.

The medicine Nobel prize 2005 was awarded to Robin Warren and Barry Marshall for their (re-)discovery of the bacterium which finally was named *helicobacter pylori*; other than earlier chance observers they had elucidated its medical significance. They encountered a rather hesitating and reluctant acceptance, and when they wanted to publish their findings, their earliest articles were rejected as incredible; even accepted papers were significantly delayed (Marshall 2006: 245). Nowadays the infection with *H. pylori* is made responsible for the majority of all stomach ulcers.

The argument for the rejection of submitted papers was the claim that no bacterium could survive the stomach acid. But really, this bacterium is able to survive, mainly because it is capable of forming biofilms (Stark et al. 1999) which protect against the acids.

Misjudgements of this type have two characteristic features:

- a certain effect or phenomenon is declared "impossible", with some catchy, apparently convincing argument, but
- it is ignored that there is a *protective mechanism* (or a *protective component*) which enables the effect or phenomenon in spite of adverse conditions.

This recurrent pattern shall be named the *helicobacter fallacy.*

4.2 The Contribution of Entanglement to Stability

In his famous book "What is Life?", Erwin Schrödinger asked which physical principles govern the stability of biological systems. In particular, he states that "incredibly small groups of atoms, much too small to display exact statistical laws, do play a dominating role in the very orderly and lawful events within a living organism". (Schrödinger 1944: 19)

Among other authors, Ogryzko comes back to this "problem of the small numbers", or, generally, our incapacity to sufficiently explain the *stability of biological order*. He recurs to the book just quoted and to Schrödinger's belief "that 'new physics' should be involved in explaining the stability of biological order". Although it was Schrödinger, too, who created the concept of quantum entanglement (Schrödinger 1935: 827), it must be fixed that he did not combine this concept with the present issue. In Ogryzko's words, "entanglement … might be most relevant in taking the leap to the quantum mechanical description of biological systems", and that, with respect to the present topic, entanglement must be taken into account. He comes to the conclusion that "entanglement can provide biology with a conceptual ingredient that had been missing from the molecular explanations of life dominating the field for the last 50 years". (Ogryzko 2008: 6, 8)

The position that entanglement plays a fundamental role in living systems will bring about theoretical and experimental challenges. The strongest antagonist of entanglement is decoherence: entanglement can persist only as long as decoherence will not prevail. Since chemical reactions are inevitably subject to environmental decoherence, the problem arises how to accommodate quantum theory for the sake of emergence and persistence of biological systems.

"If quantum mechanics is to play a non-trivial role in bio-systems, then some way to sustain quantum coherence at least for biochemically, if not biologically, significant time scales must be found." (Davies 2004: 76) But, at the same time, Davies warns against "simplistic calculations" which would over-estimate the strength of decoherence. Here we should be extremely careful in order not to run into the trap of the helicobacter fallacy (Section 4.1).

There are essentially three ways in which decoherence could be pushed back for long enough to enable biological processes to occur:

1. screening,
2. decoherence-free subspaces,
3. local heat engines.

Screening means that the system of interest can be quasi-isolated from its environment; in this way decoherence rates can be significantly reduced. Very little is known about the screening properties of biological molecules (Davies (2004), where more details can be found). Occasionally, also temperature reduction or the local heat engines are treated under the headline "screening".

A second possibility concerns *decoherence-free subspaces*. "In the effort to build a quantum computer, much attention has been given to identifying subspaces of Hilbert space that are unaffected by the coupling of the system to its environment. Paradoxically, when a system couples very strongly to its environment through certain degrees of freedom, it can effectively 'freeze' other degrees of freedom by the quantum Zeno effect, enabling coherent superpositions and even entanglement to persist." (Davies 2008: 10)

A third approach, *local heat engines*, has the advantage of being supported by a series of experiments. This concept has been developed in a series of papers by Koichiro Matsuno (1995, 1996, 2006). (The original term "*quantum* heat engine" will be explained later.) A local heat engine is a reaction cycle in a living system operating as a heat engine. The operation of such a cycle was found robust in presence of temperature gradients, and also to the flow of reactants.

A first series of experiments studied the hydrolysis of ATP molecules. It was found that organisms may exploit temperature gradients by acting as heat engines and thereby lower the temperature at specific locations. The slow release of energy from ATP molecules indicates a reduced local temperature.

Another series of experiments was based on the citric-acid cycle, one of the fundamental and best known reaction cycles in biochemistry. Simulations were performed in a flow reactor, where temperature changes were imported from outside. Although this was a mere laboratory setting – without the help of enzymes and co-enzymes – a gradual build-up of citrate was observed. The operation of the citric-acid cycle in the presence of temperature gradients was found robust even in face of adverse disturbances coming from outside.

As a result, it was found that heat engines in the form of reaction cycles do exist, and that they remain robust against adverse disturbances from outside. Their fundamental and stable character permits an extension of the notion of *quantum* first coined by Max Planck, and it has been suggestive to creating the term *quantum heat engines*. These heat engines act against decoherence, and thus can contribute to the functioning and persistence of entanglement-based processes in living systems.

In any case where the stability of biological systems leaves open questions – after all attempts of a traditional explanation have failed – it should be taken at least as a heuristic cue that a search of entanglement effects may be reasonable. This is also backed by the recent experiments summarized above (Section 3), where it has been found that entanglement can be surprisingly robust and can exist at higher temperatures than supposed before.

5 Concluding Remarks and Outlook

Although we do not yet own a straightforward criterion – that would tell us under which conditions entanglement will prevail - the material compiled here shows that there is at least a high plausibility for the active role of entanglement in living systems.

Josephson and Pallikari (1991: 205) advance the idea that "life may exist from the beginning as a cooperative whole directly interconnected at a distance by Bell-type nonlocal interactions". The quantum domain and the domain of life processes are closely related, but a more comprehensive view will show that biological systems may function more effectively than would be expected on the basis of quantum mechanics alone (Conrad et al. 1988). Partial cues in this sense, which are also conform with the increasing acceptance of macro-entanglement, may be found in a study on hypothetical 'organizing structures' and in an attempt of more general conditions for entanglement (Gernert 2004, 2005).

An example of a serious unsolved problem is the issue of the detailed mechanism governing the folding kinetics of proteins. What is unknown is the mechanism which controls the manner how protein molecules in chains of amino acids will fold together in order to give the proteins their characteristic shape. This is known in the literature as "the problem of the multiple minimum" (Anfinsen et al. 1975); it is considered one of the major problems in structural biology (Zhou et al. 1999). It seems that this hitherto unknown influence or interaction is either an undiscovered and atypical form of entanglement, or something novel which shares with entanglement its bewildering character.

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