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Temporal witnesses of non-classicality in a macroscopic biological system

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Exciton transfer along a bio-polymer is essential for many biological processes, for instance, light harvesting in photosynthetic biosystems. Here we apply a new witness of non-classicality to this phenomenon, to conclude that, if an exciton can mediate the coherent quantum evolution of a photon, then the exciton is non-classical. We then propose a general qubit model for the quantum transfer of an exciton along a bio-polymer chain, also discussing the effects of environmental decoherence. The generality of our results makes them ideal candidates to design new tests of quantum features in complex bio-molecules.

Quantum theory can in principle be applied to any physical system[1–4], regardless of scale. Its principles explain the stability of matter and are indispensable to understanding the nature of molecular bonding and the dynamics of chemical reactions. This fact, that chemistry is fundamentally quantum regardless of scale, inspired the field of quantum biology[5,6], which has now been supercharged by the rapid progress in quantum technologies[7,8].

The key hypotheses of quantum biology are: (1) that non-trivial quantum effects are present in biological systems, such as light-harvesting complexes in photosynthetic bacteria, or the DNA, or mitochondria[9–11]; (2) that quantum effects enhance biological functionalities, for example by aiding energy transfer along a bio-polymer chain[12].

To this day, experimental evidence for both hypotheses is lacking: while there are many possible quantum models for biological systems, it is difficult to make a conclusive case that classical models (e.g., coupled classical harmonic oscillators) cannot describe them too, as probing complex systems to the same accuracy as, for instance, two entangled photons, is not an easy task. Hence it is essential to find witnesses of quantum effects in biological systems, which could inform realistic experimental schemes to test the validity of the above two hypotheses. Ideally, such witnesses should rely on minimal and plausible physical principles. It is unrealistic to expect that loopholes such as the locality one will be closed when dealing with complex systems anytime soon, hence the need to rely on physical principles.

To make progress on these issues, here we apply a different strategy compared to previously proposed quantum biology tests. We shall use a recently proposed witness of quantum effects[13], to study an exciton on a generic bio-polymer, i.e., a complex biological system made by many interacting subsystems, the monomers. This witness is based on this protocol: first, one interacts with the bio-polymer via a quantum probe (photons in this case); then, by observing how the probe's dynamical evolution is mediated by the exciton on the bio-polymer, one can establish the exciton's degree of non-classicality. The key physical principle we shall assume is the conservation of energy.

We focus on energy transfer via excitons because it is key for several biological processes, e.g., photosynthesis, in different biological systems of different scales, e.g., *Fenna-Matthews-Olson (FMO) complex* or *polydiacetylene*. Furthermore, it was suggested that quantum coherence in energy transfer may be responsible for its high efficiency[14–16]. However, while fully quantum models for exciton transfer are available, classical models can equally well describe it, or are compatible with the experimental findings on the process—hence it has been difficult to assess whether it is genuinely quantum[17,18].

Here we shall use the witness of non-classicality to rule out a vast set of classical models as possible descriptions of the exciton transfer along a bio-polymer. We shall use a photon field as a quantum probe, to infer quantum features of the exciton on the bio-polymer, and indirectly of the bio-polymer itself. The strength of this approach is that it doesn't require the direct control of the bio-polymer but of the quantum probe only. This makes the argument applicable to all those biological systems that can be described as complex systems made by properly identified monomers.

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To investigate the possibility of applying this witness of quantum effects in a noisy environment, we shall also provide a qubit model of the exciton transfer on a chain of qubits, ideally describing a bio-polymer, without resorting to any dynamical assumption for the latter. This ideal model must not be understood as a detailed description of the exciton dynamics on the bio-polymer but as a general, system and scale-independent way of analysing the best conditions to observe the probe's dynamical evolution required by the witness of quantum effects. This model intends to assess whether the idea of applying the witness of non-classicality to quantum biology can be supported by an experiment on a biological system (the bio-polymer). However, a feasibility study of such an experiment would require enriching the model accordingly, which we leave for future work. This makes our information-theoretic argument general enough to be used for different systems in other fields of quantum biology.

Temporal witness of non-classicality

The word "non-classicality" shall indicate, in our paper, a specific information-theoretic property. A system M is *non-classical* if it has at least two distinct physical variables that cannot be measured to arbitrarily high accuracy by the same measuring device[19]. We call these variables "incompatible", generalising non-commuting variables in quantum theory.

A *witness of non-classicality* is a protocol to assess whether a physical system M must be described by at least two incompatible variables, by probing that system with a quantum system. The witness relies on a *witnessing task*, which is defined such that if it can be performed by the system M, then M must have two incompatible variables under given assumptions. For instance, in entanglement-based witnesses of non-classicality[19], the witnessing task is the creation of entanglement between two spatially separated subsystems Q_1 and Q_2, mediated solely by M. This witness has been applied to quantum gravity in[20,21]. The advantage of employing a witnessing task to assess the non-classicality of M lies in its implication that both non-commuting variables are essential to induce Q's dynamical evolution. Consequently, a successful witness of non-classicality would rule out all the classical models describing M that respect the specified assumptions: these classical models would rely on a single variable for M, which is insufficient to render the witnessing task possible.

Here we shall exploit a different witness[13], which can be regarded as the temporal version of the entanglement-based witness. Let us first consider, for simplicity, a system comprising a single quantum probe Q and the system under investigation M. The witnessing task for this witness is the *quantum coherent evolution* of Q driven by M, under the assumption that a global quantity on M and Q is conserved. If this task can be achieved in an actual experiment, then we can conclude that M is non-classical.

The witness relies on two assumptions: (i) The conservation of a global variable on M and Q, which must be a function of a "classical" variable Z_M pertaining to M, e.g., its energy; (ii) The formalism of quantum theory.

To illustrate the argument supporting the witness[13], we shall provide proof by contradiction that assumes, without loss of generality, Q to be a qubit, with Z_Q being its computational basis, and M to be a bit, with Z_M being its "classical" variable. We shall show that the latter assumption is in contradiction with the possibility of the witnessing task introduced above.

In order for the witnessing task to be possible, a dynamical transformation U_{MQ} must be allowed on the joint system $M \bigoplus Q$, that conserves the quantity $Z_M + Z_Q$ (as per condition (i)).

This condition requires $\left[U_{MQ}, Z_M + Z_Q\right] = 0$. If M just has one classical variable Z_M and we consider the qubit algebra, then only Hamiltonians of the form $\alpha Z_Q + \beta Z_M + \gamma Z_Q Z_M$ are allowed, where α, β, γ are real-valued. Generalisations are possible to higher dimensions when we relax the assumptions of Q being a qubit and M being a bit. In these scenarios, the Hamiltonian describing the interactions between Q and M will change to include the generators of the appropriate algebra. However, the absence of two non-compatible degrees of freedom in M will still render this interaction incapable of making Q's classical basis unsharp if it was sharp initially (In quantum physics, a variable is "sharp" when the state of the system it belongs to is in an eigenstate of that variable. Here, Z_Q is sharp on Q if the state of Q is either $|0\rangle$ or $|1\rangle$. For a more formal definition, see[29]). Hence if M can realise the witnessing task, and the assumptions are satisfied, M must have an extra, non-commuting variable—thus being non-classical, see Fig. 1.

It is important to note here that the conservation law is enforced on the *global* variable $Z_Q + Z_M$, rather than on the local variables Z_Q and Z_M. Furthermore, due to the additive form of the conserved quantity, the global

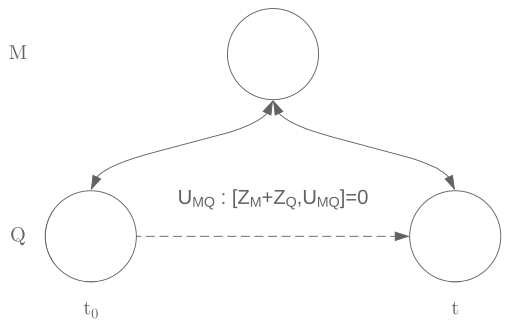

Figure 1. Pictorial representation of the temporal witness of non-classicality.

system $Q \oplus M$ can be expanded to include additional subsystems, provided that their *local* variables are included in the global conserved quantity. This makes the temporal witness of non-classicality more robust, as the model presented here can be easily extended to include an environment, provided that: (1) its local variables satisfy the global conservation law , and (2) there is a sufficiently high degree of control over its relevant degrees of freedom to exclude it from being responsible for Q's coherent evolution.

In the exciton transfer scenario, the quantum controllable system Q is a single *photon* exciting the bio-polymer at t_0, while the system M is the exciton in a molecular environment. The witnessing task is the quantum coherent evolution of the photon, mediated by the *exciton* M that is created on the bio-polymer when the photon Q is absorbed. The conservation of the *global energy* of the photon-exciton system and the molecular environment ensures that assumption (i) is satisfied. This scenario interestingly corresponds closely to experiments on exciton transfer in polydiacetylene, see e.g.[22].

A qubit model for the exciton transfer

We shall now propose a quantum model to demonstrate the possibility of the witnessing task under energy conservation in a noisy environment. This will provide the best experimental conditions to implement the temporal witness of non-classicality in a real scenario.

We shall consider a bio-polymer whose N monomers are described as a 1-d qubit chain. Here "monomer" refers to the smallest subunit of the complex system that can support an exciton alone. Experimentally, this can be initially selected according to the experimental setup, see e.g.[22]. In the Heisenberg picture, each monomer M_j is described by its components $\{X_j, Y_j, Z_j\}$, $j = 1, \ldots, N$, satisfying the Pauli algebra, where Z_j is the computational basis. We introduce the *raising* and *lowering* operators for each monomer, $\sigma_j^{\pm} = X_j \pm iY_j$, to describe them with the operators $\{\sigma_j^+, \sigma_j^-, Z_j\}$.

The chain's initial state is:

$$\rho_S = |00...0\rangle\langle 00...0| \tag{1}$$

as no excitation has been created yet.

Creation of an exciton. A photon Q creates an exciton on the chain. It is initially localised on the *first* monomer of the chain. Its quantum observables are $X_j^p, Y_j^p, Z_j^p, \alpha_j^{\pm} = X_j^p \pm iY_j^p$ and its initial state is:

$$\rho_p = |10...0\rangle\langle 10...0|. \tag{2}$$

Once the photon interacts with the first monomer, its degree of freedom is swapped with the degree of freedom of the monomer itself, so that:

$${}^0\rho_S = Tr_{\rho_p}\left[\text{SWAP}_{M_1,p}\rho_S \otimes \rho_p \text{SWAP}^{\dagger}_{M_1,p}\right] = |10...0\rangle\langle 10...0|. \tag{3}$$

Now the exciton is *localised* on the first monomer of the chain. We focus on the single exciton regime, i.e., the probability of creating a second exciton in the chain is negligible[22]. Crucially, the conservation law is satisfied by the first step of the model: $\left[\text{SWAP}_{M_1,p}, \sum_{j=1}^N Z_j + Z_p\right] = 0$.

Exciton dynamics and environment. We describe the exciton propagation with an *XX-Hamiltonian*[23]:

$$H_{XX} = \frac{1}{2}\sum_{n=1}^{N} J_n(X_nX_{n+1} + Y_nY_{n+1}) - \sum_{n=1}^{N} B_nZ_n \tag{4}$$

$$= \frac{1}{4}\sum_{n=1}^{N} J_n\left(\sigma_n^+\sigma_{n+1}^- + \sigma_n^-\sigma_{n+1}^+\right) - \sum_{n=1}^{N} B_nZ_n \tag{5}$$

where $J_n, B_n \in \mathbb{R}\ \forall\ n = 1, \ldots, N$. Notably, this model can capture different bio-polymers simply by changing J_n and B_n. Thus it can be easily extended to other phenomena, like anisotropies in the bio-polymer, next-nearest neighbours coupling and multiple dimensions. Moreover, since $\left[H_{XX}, \sum_{j=1}^N Z_j\right] = 0$, this step of the model satisfies the conservation law too, as required by the witness.

To be realistic, one must also consider the environment, which induces decoherence. Here we shall model the environment as a thermal bath, using a *quantum homogeniser*[24]. This is a reservoir of R qubits that when suitably initialised can be used to prepare a system qubit in any quantum state, to an arbitrarily high precision, improving as we increase R. The *only* unitary that can accomplish this task, called *homogenisation*, is the *partial swap* $\text{PSWAP} = \cos\eta\ \mathbf{I} + i\sin\eta\ \text{SWAP}$, where $\mathbf{I}$ is the identity operator on a two-qubit Hilbert space and η is the interaction strength between the system and the reservoir. This makes the quantum homogeniser a *universal quantum machine*[24]. Using this machine to describe the decoherence induced by a suitably prepared environment on the system, thus, doesn't affect the generality of the conclusions.

Initially, the qubits in the reservoir are all prepared in the same maximally mixed state, so that:

$${}^0\xi = \bigotimes_{j=1}^{R} {}^0\xi_j = \left[\frac{1}{2}(|0\rangle\langle 0| + |1\rangle\langle 1|)\right]^{\otimes R}. \tag{6}$$

The decoherence is modelled by the interaction between the system and the reservoir, via the partial swap, and we shall call the interaction strength η the *decoherence strength*. With this initial state for the reservoir, a

homogenisation of (at least) one of the monomers to the maximally mixed state would make that qubit effectively classical, thus not capable anymore of transmitting quantum coherence. Collision models are often applied to describe processes within a noisy environment, including decoherence. Crucially, they can offer a reliable estimation of the noise that is present in warm biological environments[25–28]. This unitary satisfies the conservation law because $\left[\text{PSWAP}, \sum_{j=1}^{N} Z_j + \sum_{l=1}^{R} Z_l\right] = 0$.

The protocol for the decohered exciton transfer works as follows. At each iteration of the protocol k, with $k = 1, \ldots, N$, *each* monomer M_j, $j = 1, \ldots, N$, undergoes the homogenisation process with the R qubits/phonons in the reservoir. This is the *decoherence phase*, see Fig. 2a). When the homogenisation has been performed on all the monomers, i.e., the decoherence round has ended, the monomer M_k *transfers* its quantum state to the monomer M_{k+1}. This is the *transfer phase* of the protocol, see Fig. 2b). After the transfer phase, the protocol can be repeated for the $(k+1)-$ th iteration. This explains the notation: the upper script 0 in ${}^0\rho_S$ and ${}^0\xi$ refers to the state of the system and the reservoir, respectively, *before* the protocol begins, at $k = 0$.

We shall introduce two different models for the reservoir in this scenario: (1) *Markov Environment*: we re-initialise the quantum homogeniser in the maximally mixed state ${}^0\xi$ whenever a new monomer is involved in the decoherence phase of the protocol, at every iteration; (2) *Non-Markov Environment*: the reservoir is *never* re-initialised, neither when a new monomer enters the decoherence phase nor when a new iteration of the protocol begins.

Exciton recombination. At the end of the $N-$ th iteration, we model recombination by swapping again the spatial degrees of freedom of the bio-polymer and that of the photon. The witnessing task is performed if the photon is *quantum coherently delocalised* on every monomer of the chain:

$$\begin{aligned}\rho_p = &p_{0,0}|00...00\rangle\langle 00...00| + p_{1,0}|10...00\rangle\langle 00...00| + \\ &+ p_{0,1}|00...00\rangle\langle 10...00| + ... + p_{N,N}|00...01\rangle\langle 00...01|;\end{aligned} \tag{7}$$

This dynamics provides the coherent evolution required by the temporal witness of non-classicality.

To determine experimentally whether the witnessing task is achieved, one can measure the position of the photon with an interference experiment: observing interference fringes and assuming the conservation law of the additive quantity $\sum_{j=1}^{N} Z_j + \sum_{l=1}^{R} Z_l + Z_p$, the witness allows us to conclude that the exciton, and hence the bio-polymer, is non-classical. We stress here that the conservation law is enforced on the *whole* system made by the N monomers, the R reservoir qubits and the photon. This means that one can consider a change in the Z component of one subsystem if it is balanced by an equal and opposite change in the Z component of the other subsystems.

Markovian vs Non-Markovian environment

Here we derive the final state of the photon in the framework of both a *Markovian* and a *Non-Markovian* environment. The former is equivalent to having a different reservoir per monomer at each iteration of the protocol, the latter to a reservoir evolving with the bio-polymer. This is the Non-Markovian feature of the model (different from other models, e.g., in[29]): the state of each reservoir qubit has "memory", and it cannot be re-initialised at every iteration. We assume for simplicity that the system is an $N = 3$ monomer chain and the reservoir is made of $R = 3$ qubits. Every reservoir is initialised in the maximally mixed state in Eq. (6), while the bio-polymer is initially in the state in Eq. (3). The final state of the photon after the exciton recombination in the Markovian scenario is (See Supplementary Information, Chapter 1, for a detailed analytical derivation):

$$\begin{aligned}{}^3\rho_p = &\left[{}^3\rho_{p_1} \otimes {}^3\rho_{p_2} + itJ_1 \cos^{18}\eta\left(\alpha_1^+\alpha_2^- - \alpha_1^-\alpha_2^+\right) - t^2 B_2\left(\alpha_1^+\alpha_2^- + \alpha_1^-\alpha_2^+\right)\right] \otimes {}^3\rho_{p_3} \\ &- t^2 J_1 J_2 \cos^{18}\eta\left(Z_2 + \cos^{12}\eta\right)\left(\alpha_1^+\alpha_3^- + \alpha_1^-\alpha_3^+\right),\end{aligned} \tag{8}$$

while in the Non-Markovian scenario is (See Supplementary Information, Chapter 2, for a detailed analytical derivation):

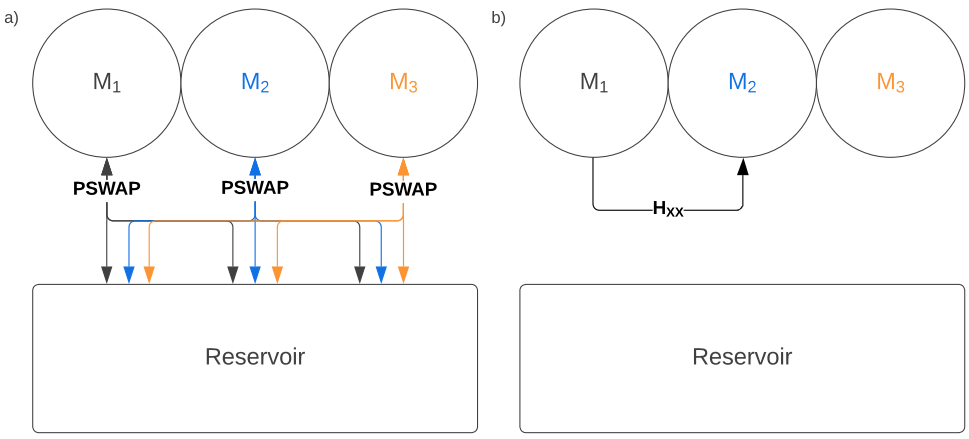

Figure 2. Schematic representation of the protocol: (**a**) decoherence phase; (**b**) transfer phase.

$$
\begin{aligned}
{}^{3}\rho_{p} = {}& {}^{3}\rho_{p_1} \otimes {}^{3}\rho_{p_2} \otimes {}^{3}\rho_{p_3} \\
& + itJ_1[F(\eta) + 2itB_2G(\eta)]\left(\alpha_1^+\alpha_2^- - \alpha_1^-\alpha_2^+\right) \otimes {}^{3}\rho_{p_3} \\
& + itJ_1[G(\eta) + 2itB_2F(\eta)]\left(\alpha_1^+\alpha_2^- + \alpha_1^-\alpha_2^+\right) \otimes {}^{3}\rho_{p_3} \\
& - \frac{1}{2}t^2J_1J_2\left(Z_2 + \cos^{12}\eta + s(\eta)\right)\left[F(\eta)\left(\alpha_1^+\alpha_3^- + \alpha_1^-\alpha_3^+\right) + G(\eta)\left(\alpha_1^+\alpha_3^- - \alpha_1^-\alpha_3^+\right)\right]
\end{aligned}
\tag{9}
$$

where ${}^{3}\rho_{p_j}$ is the density matrix of the photon localised on the monomer M_j at the $k = 3$ iteration of the protocol, $F(\eta)$, $G(\eta)$ and $s(\eta)$ are defined in Supplementary Eq.76, Supplementary Eq.77 and Supplementary Eq.79, respectively.

Discussion

We shall now compare the two states for the Markov (Eq. 8) and Non-Markov (Eq. 9) environments.

In the weak coupling limit, in both scenarios, the exciton mediates a coherent delocalisation of the photon over the bio-polymer. Hence the witnessing task is successfully achieved, even in the presence of decoherence. Using the temporal witness of non-classicality, one can conclude that the exciton mediating the photon coherent delocalisation is non-classical, and so the process governing its transfer along the bio-polymer must be non-classical itself. This is the key result of the work, which opens the possibility of applying the temporal witness of non-classicality introduced here to the field of quantum biology, providing a novel tool to discriminate conclusively the role of quantum effects in biological processes.

The model explains why, despite decoherence, a coherent delocalisation of the exciton over the chain is still possible: the interactions between the monomers mitigate the decoherence, preventing ${}^{k}\rho_S$ from becoming an eigenstate of H_{XX} in Eq. (5).

Interestingly, at every time step, the exciton can face three different scenarios: (1) It can remain localised on the monomer preceding that involved in the transfer phase, as suggested by the coefficients B_j; (2) It can (coherently) hop on to the next monomer. This can occur via two mechanisms: (2.1) Via the intermediate monomers, see Fig. 3a). This is mathematically expressed by the terms in Eqs. (8) and (9) that are proportional to Z_j: since Z_j is conserved throughout the process, the exciton moves across the monomer M_j leaving it globally unaltered; (2.2) Via the reservoir, see Fig. 3b). One can see this mechanism in Eq. (8) and in Eq. (9) in the terms proportional to $\cos^{12}\eta$ and $\cos^{12}\eta + s(\eta)$, respectively. Recalling that the interaction between the polymer and the reservoir is described as a pswap, for the transfer to occur in a Markovian scenario, the swap between the reservoir qubit and the monomer must *not* be performed at any step as this would put the monomer in a maximally mixed state, blocking the coherent evolution of the exciton on the polymer. This occurs with probability $\cos^2\eta$ at every protocol's iteration. In a fully Non-Markovian scenario, instead, the environment can also exchange information with the chain, leading to active involvement in the coherent evolution of the exciton, which is described by the additional $s(\eta)$. We notice that the preceding monomers are not involved here: the environment is solely responsible for the quantum coherent delocalisation of the exciton.

The difference between a Markov and a Non-Markov environment, therefore, lies in the amount of coherence maintained by the qubits. Such coherence (i) creates, at every iteration, a second "hopping term" between the two monomers involved in the transfer phase, shifted by a phase factor $e^{i\pi}$; (ii) reshapes the probabilities for the coherent delocalisation of the exciton over the bio-polymer.

Consider now the coefficients of the terms describing the aforementioned mechanisms.

Concerning the coefficients describing the coherent delocalisation of the exciton *via the chain* (mechanism (2.1)), Figs.4 and 5 show that in the weak coupling regime (i) $F(\eta)$ and the coefficient in the Markov scenario are equal, and this holds true at every step of the protocol and (ii) $G(\eta)$ appears to be very small, almost negligible,

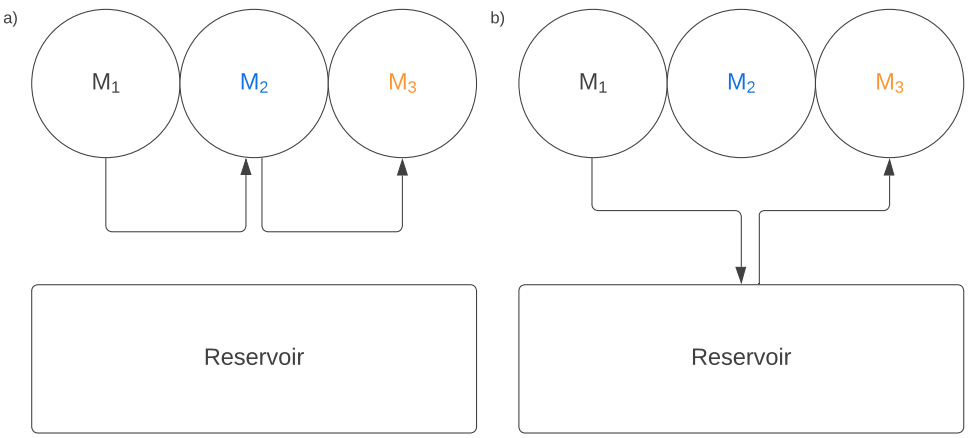

Figure 3. Schematic view of the coherent hopping mechanisms: (**a**) via intermediate monomers; (**b**) via reservoir.

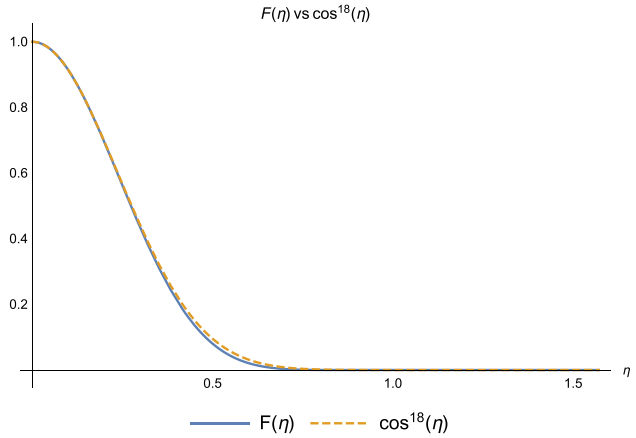

Figure 4. Coefficients $F(\eta)$ (blue) and $\cos^{18}\eta$ (orange) at the end of $k = 2$ iteration.

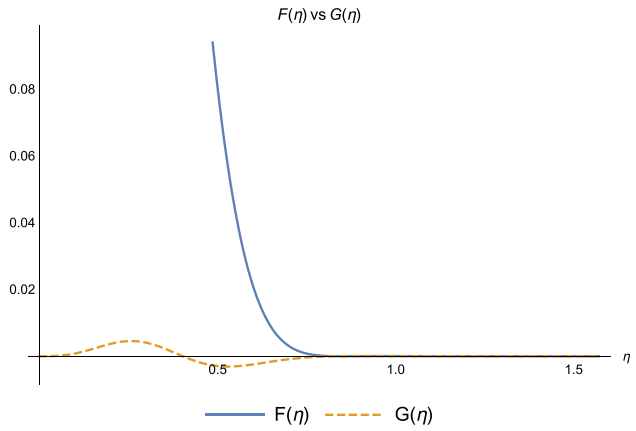

Figure 5. Coefficients $F(\eta)$ (blue) and $G(\eta)$ (orange) at the end of $k = 2$ iteration.

thus its effect is *practically* negligible (See Supplementary Information, Chapter 3, to check the numerical values of the coefficients at every step of the protocol, for different values of the decoherence parameter η both in the weak and strong coupling regimes): small values of η make the interaction with the environment very unlikely, therefore it cannot mediate the exciton transport along the bio-polymer. This elucidates why the coefficient $F(\eta)$ has the same value as its Markovian counterpart at every step of the protocol.

Moreover, for some values of η, both $F(\eta)$ and $G(\eta)$ are vanishing: the hopping via chain is *prevented* by the strong coupling with the environment. The effect of decoherence is so strong that the monomers lose coherence as soon as they interact with the environment. They effectively become equivalent to classical bits and not capable of quantum-coherently transmitting the exciton anymore.

Considering the role played by the Non-Markovian environment in (2.2), i.e., the hopping mechanism *via the reservoir*, the same argument as before applies, focusing on the coefficients $s(\eta)$ and $\cos^{12}\eta$. They have almost the same numerical values as in the *weak coupling* regime, as one can see in Fig. 6. As soon as the coupling with the environment increases, entering the *strong coupling* regime, the hopping via reservoir becomes impossible with a Markovian environment, but it is still possible with a Non-Markov environment. Informally, one can say that the coherence "stored" by a Non-Markov environment is then used by the bio-polymer for the quantum coherent delocalisation of the exciton.

This is clarified by Fig. 7: entering the strong coupling regime, the coefficient $s(\eta)$ describing the coherence exchange between system and environment becomes larger than the $\cos^{12}\eta$, which instead describes a passive role of the environment in the exciton transport on the chain. Hence the Non-Markovian environment becomes *crucial* for the energy transfer in the strong coupling regime, as no other hopping mechanism is allowed. This may explain why bio-polymer vibrations may be relevant in exciton-mediated transport phenomena, such as light-harvesting[30–34].

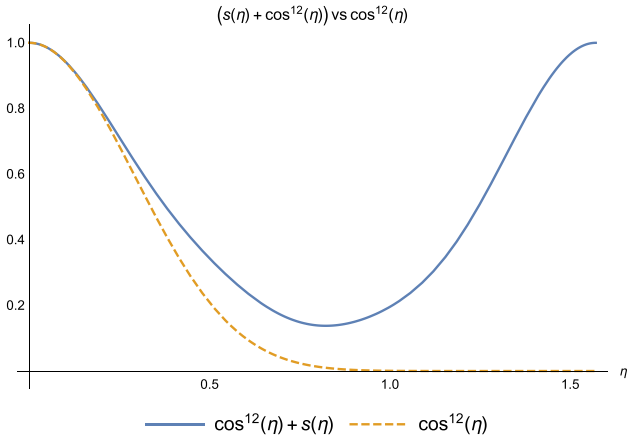

Figure 6. Coefficients $s(\eta) + \cos^{12}(\eta)$ (blue) and $\cos^{12}(\eta)$ (orange) at the end of $k = 2$ iteration.

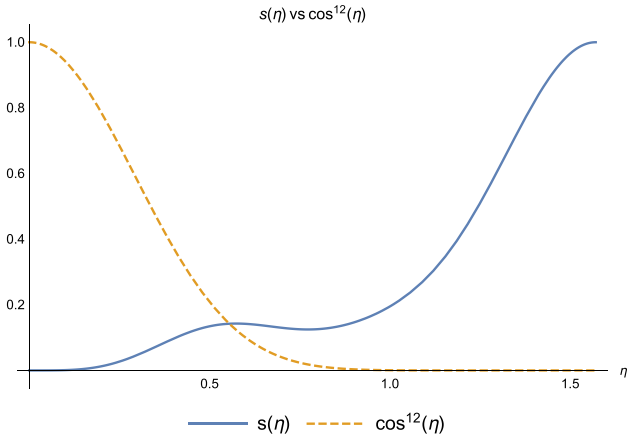

Figure 7. Coefficients $s(\eta)$ (blue) and $\cos^{12}(\eta)$ (orange) at the end of $k = 2$ iteration.

Conclusions

We have proposed a novel experimental scheme to witness non-classicality in the exciton transfer on a bio-polymer, using a photonic quantum probe. This witness is subtly different from other ones, e.g.[35–37], as it investigates an *intrinsic*, more *general*, property of the biological system itself, rather than of the specific process. This witness has the appeal of being very broadly applicable and of relying only on a few general assumptions: energy conservation and the formalism of quantum theory. One in fact could relax the latter and recast this witness of non-classicality in the information-theoretic framework known as *constructor theory of information*[38]. This dynamics-independent approach would achieve full generality in our argument, giving interesting insights regarding possible *physical* reasons why biological systems must be non-classical[39]. We shall explore this in a forthcoming paper.

We have also provided a qubit model to discuss the possibility of the witnessing task, namely the quantum coherent evolution of the photon probe, with an analysis of decoherence, in the Markovian and Non-Markovian regimes. The model shows that the witnessing task is always possible, even in the presence of decoherence, and it does so in a system and scale-independent way. The generality of the model makes it suitable to describe several existing quantum biology results[14,40,41]. This shows that the application of the temporal witness of non-classicality[13] is meaningful in the field of quantum biology and it could shed new light on the importance of quantum effects in biological systems. Future investigations on the possibility of designing an experiment with a real biological system can benefit from the results discussed in this work, using this model as a starting point to be enriched with system-specific features. For example, the structure of the environment presented in this work is similar to the one considered in[42], where molecular dynamics simulations are employed to study the coupling between the protein environment and the vertical excitation energies in a real biological system. Enriched with the results discussed in this paper, the same simulation could be used to explore the applications of the temporal witness of non-classicality to a more realistic system.

The role of a Non-Markovian environment in the witnessing task becomes essential in the strong coupling regime: the only way for the witnessing task to be possible when $\eta = \frac{\pi}{2} \approx 1.571$ is to rely on the interaction of the bio-polymer with its own *Non-Markovian* environment. This is because the reservoir has memory of the

occurred process and maintains coherence throughout it. Instead, in a weak coupling scenario, the witnessing task is possible *independently of the Markovianity* of the reservoir. This conclusion is intuitively pleasing since in the strong coupling regime the separation between the system and environment becomes nonphysical and it is more appropriate to think of the environment as being part of the system.

The generality of our witnessing scheme makes it an ideal candidate for designing new experiments in quantum biology, to pin down conclusively the role of quantum effects in exciton transfer and other energy transfer processes. We leave the development of this research to future work, to enrich this idealised model with system-specific dynamical features to make it capable of informing the *feasibility* of the witnessing task in a real system, not only its possibility.

Data availibility

All data generated or analysed during this study are included in this published article and its Supplementary Information file.

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Author contributions

All the authors contributed equally to the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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