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RESEARCH ARTICLE

RESONANCE-COHERENCE SEPARATION IN MOLECULAR ENERGY TRANSFER: AN OPEN QUANTUM-SYSTEM FRAMEWORK

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ABSTRACT

Resonant energy transfer in molecular systems can remain efficient under substantial environmental dephasing, making transport enhancement alone an insufficient indicator of persistent quantum coherence. A central question is whether the environmental scale governing the disappearance of coherence-sensitive behaviour coincides with the scale governing the loss of resonance-enhanced transfer. This work develops an open quantum-system framework for examining that separation in a weakly driven donor-bridge-acceptor molecular network. The model incorporates coherent intermolecular coupling, external resonant excitation, population relaxation, pure dephasing and irreversible acceptor trapping. Transfer efficiency, time-averaged quantum coherence and resonance enhancement are evaluated systematically as functions of environmental dephasing. The numerical analysis identifies two distinct operational scales. The selected coherence threshold occurs at

$$\Gamma_{\text{coh}} = 0.1431J$$

whereas the resonance-survival threshold occurs at

$$\Gamma_{\text{res}} = 1.5294J.$$

Their difference,

$$\Delta\Gamma_{\text{RC}} = 1.3863J,$$

defines a finite resonance-coherence separation regime in which resonance-enhanced molecular energy transfer persists after the selected coherence measure has fallen below its operational threshold. In the baseline model, the resonance-survival scale is approximately 10.7 times the corresponding coherence threshold. These results demonstrate that resonance survival and coherence survival need not occur on the same environmental scale. The framework provides a quantitative method for separating persistent resonance-mediated transport from the persistence of measurable quantum coherence and may be applicable to excitonic, vibrational, photochemical and externally driven molecular networks.

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INTRODUCTION

Resonant energy transfer is fundamental to molecular photophysics, excitonic transport, vibrational dynamics and a wide range of light-driven chemical processes. Yet resonance itself is not a uniquely quantum phenomenon. Classical coupled oscillators can display frequency selectivity, phase-dependent response, mode hybridisation and enhanced energy exchange near resonance. Molecular systems add a further layer of complexity because the same observable transfer process may also involve coherent superpositions, electronic-vibrational coupling and interference between competing pathways. Recent work has therefore moved beyond asking whether coherence exists and increasingly asks when coherence produces experimentally distinguishable dynamical behaviour (1,2). This distinction is particularly important because efficient transport is not equivalent to quantum transport. Coherence can alter electron-transfer pathways and modify the interference between alternative molecular channels (3). Strongly coupled molecular and photonic systems also provide regimes in which excitation transport acquires collective or hybrid characteristics that are not adequately described by simple hopping pictures (4). At the same time, modern treatments of open quantum dynamics increasingly emphasise that the system and its environment must be considered together when assessing the persistence and functional relevance of coherence (5). The environmental contribution is not characterised by a single universal decay law. Molecular spectral densities can possess substantial structure, and their high-frequency components may alter the timescales over which quantum information is lost (6). Correspondingly, molecular coherence can exhibit exponential, Gaussian or more complicated decay depending on the character of system-environment coupling (7). These observations make it difficult to assign a universal boundary separating quantum-coherent from effectively classical molecular motion. Light-matter interactions provide one of the most direct experimental routes for preparing and probing such coherent molecular dynamics (8). However, detecting coherence and demonstrating that an observed transport process requires coherence are different tasks. Recent theoretical

work on optimal excitation-energy transfer has highlighted this distinction by examining the separate roles of coherence, entanglement and collective dissipative processes in transport performance (9). An important consequence is that high transfer efficiency alone cannot be regarded as an unambiguous quantum signature. Photosynthetic and biomolecular systems provide particularly rich examples because electronic, vibrational and environmental timescales can overlap. Exciton-vibrational energy dissipation has recently been associated with phase synchronisation capable of sustaining comparatively long-lived coherence in photosynthetic antennas (10). Ultrafast measurements of nicotinamide adenine dinucleotide have similarly indicated coherent sub-100-fs energy transfer assisted by a charge-transfer state (11). Such results demonstrate that population transfer can depend on coupled electronic and nuclear dynamics rather than on a single incoherent rate constant. Theoretical descriptions must therefore account explicitly for dissipation. Recent open-system approaches allow individual pathways of energy loss and environmental interaction to be quantified within a common dynamical framework (12). Their extension to non-Markovian environments shows that environmental memory can influence not only the decay rate of coherence but also the apparent direction and timing of energy exchange (13). Consequently, a simple increase of a phenomenological dephasing constant may not capture every physically relevant route from coherent to incoherent dynamics. Hierarchical-equation methods provide a complementary description of structured molecular environments. Recent work relating hierarchical equations of motion to quantum-information concepts has helped clarify the behaviour of coherence and information flow along open-system trajectories (14). Path-integral formulations incorporating Lindblad-type gain and loss processes provide another route for modelling molecular systems subject simultaneously to coherent evolution and irreversible environmental interactions (15). Memory effects are also directly relevant to transport performance. Energy-transfer efficiency in noisy molecular systems can depend on the temporal correlations of the environment rather than only on the overall magnitude of fluctuations (16). This is significant for the quantum-classical problem because two systems exhibiting similar average energy transfer may retain very different amounts of phase information.

The physical environment can additionally reshape resonant transfer itself. Tip-enhanced molecular energy transfer illustrates how a local electromagnetic structure can modify molecular coupling and transfer pathways (17). Molecular polariton systems provide a broader example in which strong light-matter coupling produces hybrid states with transport properties qualitatively different from those of uncoupled molecular excitations (18). These developments motivate theoretical criteria that are sufficiently general to distinguish transport enhancement from the microscopic mechanism producing it. Related open-system questions now extend beyond conventional molecular photophysics. Excitonic quantum-battery models, for example, provide controlled settings in which coherent coupling, energy storage and dissipation can be examined simultaneously (19). Molecular aggregates also exhibit systematic changes in relaxation behaviour as intermolecular coupling and collective structure are varied (20). Nonadiabatic molecular-dynamics simulations further demonstrate that excitonic transport may arise through a continuously evolving interplay between electronic coupling and nuclear motion (21). Comparable complexity is found in biological light-harvesting systems. Theoretical analysis of excitation transport in the PE555 complex continues to reveal sensitivity to site energies, coupling strengths and environmental interactions (22). At the same time, advances in ultrafast structural probes are making increasingly direct interrogation of molecular quantum coherence possible (23). These experimental developments strengthen the need for theoretical observables that can distinguish coherence itself from consequences that can also emerge in classical dynamics. A useful perspective is therefore to treat decoherence as a dynamical process with identifiable pathways rather than as a binary disappearance of quantumness. Mapping of molecular decoherence pathways has shown how specific structural and environmental contributions can govern loss of electronic coherence (24). This view is consistent with the broader modern treatment of quantum biology, where the central scientific question is not whether molecular systems obey quantum mechanics, but whether particular quantum features remain functionally or experimentally distinguishable under realistic environmental conditions (25). Reduced open-system descriptions provide a practical framework for addressing this question. The Lindblad master equation offers a widely used representation of Markovian dissipation and decoherence and provides a transparent starting point for constructing controlled molecular-network models (26). Within such models, coherence need not be inferred from population oscillations alone. It can be quantified using established resource-theoretic measures (27), including the ℓ_1 -norm of coherence based on off-diagonal density-matrix elements (28). Experimental and theoretical studies of light-harvesting complexes established much of the foundation for this distinction. Single-complex measurements revealed coherent characteristics along alternative excitation pathways (29), while multidimensional spectroscopic studies identified signatures associated with coherent energy transfer and the accompanying challenge of distinguishing electronic from vibrational contributions (30). These observations motivated extensive investigation of the competing roles of coherence and environmental noise.

One important outcome of this research is the recognition that environmental coupling need not simply suppress transport. Noise-assisted mechanisms can enhance energy-transfer performance over particular ranges of dephasing (31). Experiments reporting long-lived coherence at physiological temperatures further demonstrated that molecular environments do not necessarily destroy phase information instantaneously (32). Coherent excitation dynamics have likewise been observed in photosynthetic marine algae at ambient temperature (33), while theoretical investigations have explored whether entanglement and related non-classical correlations may accompany excitation transport (34). Theoretical descriptions subsequently developed toward a unified treatment of coherent and incoherent dynamics. Reduced-density-matrix calculations showed how coherence could persist despite significant environmental interaction (35), while hierarchical approaches provided a framework capable of interpolating between coherent motion and incoherent hopping (36). Correlated environmental fluctuations were further shown to alter the transition between these regimes (37). A particularly important insight for the present work emerged from studies of noise-assisted transport. Environmental fluctuations can sometimes improve excitation transfer even as they reduce phase coherence (38). Environment-assisted quantum-transport models demonstrate that moderate dephasing can increase transfer to a target state (39). Dephasing-assisted transport in quantum networks provides a related example in which environmental interactions suppress unfavourable interference and thereby improve transport (40).

Quantum-walk models of photosynthetic transport likewise show that environmental coupling can contribute constructively to transfer under appropriate conditions (41). Coherent resonance-energy-transfer theory establishes the complementary limit in which a purely incoherent hopping treatment becomes insufficient (42). Early experimental evidence for wave-like energy transfer in photosynthetic systems played a central role in motivating these theoretical developments (43). Taken together, this literature reveals a subtle but important problem. The disappearance of a coherence-sensitive observable need not coincide with the disappearance of resonance-enhanced transport. A system may retain a strong frequency-selective or transfer-enhancing response even after environmental dephasing has reduced the selected coherence-sensitive observable below its adopted operational threshold. Conversely, the presence of oscillatory or resonantly enhanced population transfer does not alone establish that a uniquely quantum mechanism remains experimentally distinguishable. The mathematical description adopted here is grounded in the theory of completely positive open-system dynamics. Lindblad established the generator structure of Markovian quantum dynamical semigroups (44), while Gorini, Kossakowski and Sudarshan independently derived the corresponding form for finite-dimensional quantum systems (45). These results provide the formal basis for incorporating relaxation and pure dephasing into the reduced molecular dynamics considered below. The specific question addressed in this work is therefore narrower than the general problem of quantum-to-classical crossover: Does the environmental dephasing scale at which the selected coherence-sensitive observable falls below its operational threshold coincide with the scale at which resonant energy-transfer enhancement itself disappears?

We hypothesise that the two scales need not coincide. To examine this proposition, the present study develops a minimal open quantum molecular network and introduces a matched dissipative classical oscillator network as a reference framework. The quantum-system observables are used to determine the coherence-loss and resonance-survival thresholds, while the classical model provides a basis for future direct comparison of quantum and classical transfer dynamics. Two characteristic thresholds are then defined. The first, Γ_{coh} , denotes the environmental-dephasing scale at which the selected time-averaged coherence measure falls below a prescribed operational criterion. The second, Γ_{res} , denotes the scale at which resonance-induced transfer enhancement falls below its corresponding operational threshold.

When

$$\Gamma_{\text{res}} > \Gamma_{\text{coh}}, \quad (1)$$

a finite interval exists in which resonance enhancement persists after the selected coherence measure has fallen below its adopted operational criterion. We refer to this interval as the resonance-coherence separation regime.

Its width is defined as

$$\Delta\Gamma_{\text{RC}} = \Gamma_{\text{res}} - \Gamma_{\text{coh}}. \quad (2)$$

Unlike a conventional coupling-to-decoherence ratio, $\Delta\Gamma_{\text{RC}}$ is intended to quantify the separation between two physically different losses: the loss of coherence relative to the selected operational criterion and the loss of resonance-enhanced transport. The novelty of the present framework lies in separating the loss of the selected coherence-sensitive response from the loss of resonant transport enhancement within the same open quantum-system model. Rather than inferring the transition solely from declining transfer efficiency, coherence and resonance enhancement are tracked independently. This makes it possible to ask whether a measurable intermediate regime exists in which molecular resonance continues to enhance transport after the selected coherence-sensitive observable has fallen below its adopted operational threshold. The objectives of this study are therefore fourfold. First, we construct matched quantum and classical descriptions of a resonantly coupled molecular network. Second, we determine separate operational thresholds for loss of coherence-sensitive distinguishability and loss of resonance enhancement. Third, we quantify the resulting resonance-coherence separation regime for the baseline model. Finally, we identify experimentally accessible observables capable of distinguishing resonance persistence from genuinely coherence-dependent molecular dynamics. The framework is deliberately species-independent. It is intended not as a microscopic description of one particular molecule but as a controlled theoretical model for excitonic, vibrational, photochemical and externally driven molecular networks. This abstraction allows the central question to be isolated: how far can resonant molecular transport persist beyond the point at which its quantum-coherent character is no longer experimentally distinguishable?

Theoretical Framework and Methods

Quantum molecular-network model: To examine the separation between loss of quantum coherence and loss of resonance-enhanced transfer, we consider a minimal donor-bridge-acceptor molecular network. The localised single-excitation basis is

$$|D\rangle, |B\rangle, |A\rangle,$$

with $|0\rangle$ denoting the ground state. The system Hamiltonian is

$$H_S = \hbar \sum_{j=D,B,A} \omega_j |j\rangle\langle j| + \hbar J_{DB}(|D\rangle\langle B| + |B\rangle\langle D|) + \hbar J_{BA}(|B\rangle\langle A| + |A\rangle\langle B|) \quad (3)$$

where ω_j are the local excitation frequencies and J_{DB} and J_{BA} are coherent coupling strengths. Direct donor-acceptor coupling is neglected in the baseline model so that transfer occurs through the bridge. The donor is weakly driven by a monochromatic field. Under the rotating-wave approximation, the effective Hamiltonian in the rotating frame is written as

$$H_R = \hbar \sum_{j=D,B,A} \Delta_j |j\rangle\langle j| + \hbar J_{DB} (|D\rangle\langle B| + |B\rangle\langle D|) + \hbar J_{BA} (|B\rangle\langle A| + |A\rangle\langle B|) + \frac{\hbar \Omega_R}{2} (|D\rangle\langle 0| + |0\rangle\langle D|) \quad (4)$$

where $\Delta_j = \omega_j - \omega_L$ denotes detuning from the external driving frequency ω_L , and Ω_R is the weak-drive Rabi frequency. The molecular network is treated as an open quantum system using a Lindblad master equation (26),

$$\frac{d\rho}{dt} = -\frac{i}{\hbar} [H_R, \rho] + \sum_j \gamma_j \mathcal{D}[|0\rangle\langle j|] \rho + \sum_j \Gamma_{\phi,j} \mathcal{D}[|j\rangle\langle j|] \rho + \kappa \mathcal{D}[|S\rangle\langle A|] \rho, \quad (5)$$

with

$$\mathcal{D}[L]\rho = L\rho L^\dagger - \frac{1}{2}(L^\dagger L\rho + \rho L^\dagger L). \quad (6)$$

Here, γ_j denotes population relaxation, $\Gamma_{\phi,j}$ pure dephasing, and κ irreversible trapping from the acceptor into a sink state $|S\rangle$. The Lindblad construction is grounded in the standard theory of completely positive quantum dynamical semigroups (44,45).

For the baseline calculations, equal coupling and dephasing are used,

$$J_{DB} = J_{BA} = J, \Gamma_{\phi,D} = \Gamma_{\phi,B} = \Gamma_{\phi,A} = \Gamma_{\phi}. \quad (7)$$

This reduces the number of free parameters and allows the influence of decoherence to be isolated. The system is initially taken to be in the ground state,

$$\rho(0) = |0\rangle\langle 0|$$

Excitation is subsequently introduced through the weak monochromatic drive applied to the donor. This initial condition is used for all calculations unless otherwise stated. The structure of the minimal donor-bridge-acceptor open quantum-system model is illustrated in Figure 1.

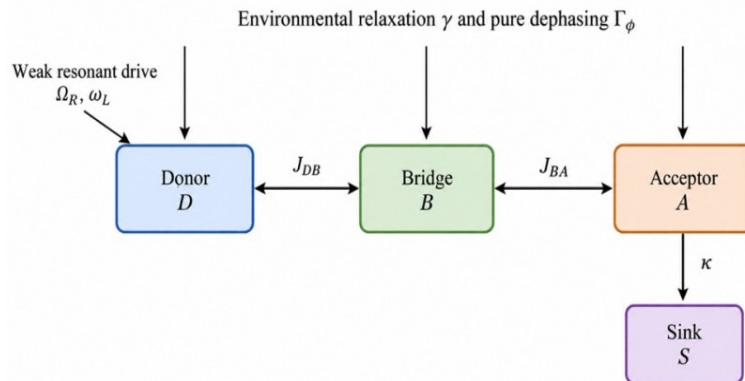


Figure 1. Minimal open quantum-system model of resonant molecular energy transfer

The donor D is weakly excited by a monochromatic external field characterised by the Rabi frequency Ω_R and driving frequency ω_L . Coherent excitation transfer proceeds sequentially through the donor-bridge coupling J_{DB} and bridge-acceptor coupling J_{BA} . Each molecular site is subject to population relaxation at rate γ and pure dephasing at rate Γ_{ϕ} . Excitation reaching the acceptor A is irreversibly transferred to the sink state S at trapping rate κ .

The instantaneous population of site j is

$$P_j(t) = \langle j | \rho(t) | j \rangle. \quad (8)$$

The quantum transfer efficiency over an observation interval T is obtained from the acceptor-to-sink flux,

$$\eta_Q = \kappa \int_0^T P_A(t) dt. \quad (9)$$

Quantum coherence is quantified using the established l_1 -norm of coherence (27,28),

$$C_{l_1}(t) = \sum_{j \neq k} |\rho_{jk}(t)|, \quad (10)$$

where the summation is taken over the donor-bridge-acceptor single-excitation subspace, $j, k \in \{D, B, A\}$,

and its time average

$$\bar{C} = \frac{1}{T} \int_0^T C_{l_1}(t) dt. \quad (11)$$

Resonance enhancement is measured by comparing transfer under resonant and deliberately detuned conditions,

$$R_Q = \frac{\eta_Q^{(\text{res})} - \eta_Q^{(\text{off})}}{\eta_Q^{(\text{off})}}. \quad (12)$$

A positive R_Q therefore indicates that resonance improves transfer, irrespective of whether the dynamics remain strongly coherent. This distinction is important because environmental noise can enhance transport while simultaneously reducing coherence (38,39).

Classical reference model and operational crossover criteria: As a reference framework for future quantum-classical comparison, the quantum system is accompanied by a matched network of three coupled damped oscillators,

$$\ddot{x}_j + 2\gamma_j^{(c)} \dot{x}_j + \omega_j^2 x_j + \sum_k K_{jk} (x_j - x_k) = F_j(t), \quad (13)$$

where the classical oscillator frequencies, coupling strengths, damping rates and driving conditions are parameter-matched to the corresponding characteristic scales of the quantum model.

The classical acceptor response is evaluated from its oscillator energy,

$$E_A^{(c)}(t) = \frac{1}{2} \dot{x}_A^2 + \frac{1}{2} \omega_A^2 x_A^2. \quad (14)$$

For future direct comparison of the quantum and classical transfer trajectories, we define the normalised discrepancy

$$\mathcal{D}_{QC} = \left[\frac{\int_0^T (\tilde{P}_A^{(Q)} - \tilde{P}_A^{(C)})^2 dt}{\int_0^T (\tilde{P}_A^{(Q)})^2 dt + \epsilon} \right]^{1/2}, \quad (15)$$

where the tildes denote normalised responses and ϵ is a small numerical regularisation term. This quantity is introduced as a comparative diagnostic and is not used to determine the numerical thresholds reported in the present study. Two characteristic environmental scales are extracted from the numerical sweeps. The coherence threshold, Γ_{coh} , is defined as the dephasing strength at which the time-averaged l_1 -coherence falls below the selected operational criterion. The resonance-survival threshold, Γ_{res} , is defined independently as the dephasing strength at which resonance enhancement falls below its corresponding operational criterion. The numerical thresholds reported here are extracted directly from the quantum-system observables. The classical model is retained as a reference framework for future direct trajectory-level comparison. The central quantity introduced in this work is therefore

$$\Delta\Gamma_{\text{RC}} = \Gamma_{\text{res}} - \Gamma_{\text{coh}}. \quad (16)$$

When

$$\Delta\Gamma_{\text{RC}} > 0, \quad (17)$$

A finite resonance-coherence separation regime exists in which resonance-enhanced energy transfer persists after the selected coherence measure has fallen below its adopted operational threshold.

Numerical protocol: All calculations are first performed in dimensionless units using J as the reference frequency scale and J^{-1} as the corresponding time scale. The baseline parameter set is shown in Table 1.

Table 1. Baseline numerical parameters

Parameter	Symbol	Baseline value
Donor-bridge coupling	J_{DB}/J	1.0
Bridge-acceptor coupling	J_{BA}/J	1.0
Drive amplitude	Ω_R/J	0.10
Detuning	Δ/J	0
Relaxation rate	γ/J	0.05
Pure dephasing	Γ_ϕ/J	Variable
Trapping rate	κ/J	0.20
Observation interval	JT	100

For each parameter set, the quantum master equation and matched classical equations are integrated over the same observation interval. The principal quantities recorded are

$$\eta_Q, \bar{C}, R_Q, \mathcal{D}_{QC}. \quad (18)$$

The dephasing strength is then swept systematically to determine Γ_{coh} , Γ_{res} , and $\Delta\Gamma_{\text{RC}}$. The present analysis focuses on the baseline parameter set defined in Table 1. Numerical robustness is assessed through integration-tolerance checks and interpolation consistency of the extracted thresholds. The principal numerical test is therefore straightforward: if

$$\Gamma_{\text{res}} \approx \Gamma_{\text{coh}},$$

the proposed separation regime is absent or negligible. If instead

$$\Gamma_{\text{res}} > \Gamma_{\text{coh}},$$

the baseline model exhibits a finite resonance-coherence separation regime in which resonance enhancement persists beyond the adopted coherence threshold.

RESULTS

The open quantum-system equations defined were numerically integrated using the baseline parameter set in Table 1. All results reported below are deterministic outputs of the theoretical model. No experimental or externally sourced numerical data were used.

Effect of dephasing on molecular coherence and energy transfer: The baseline resonant donor-bridge-acceptor network was first evaluated as a function of the pure-dephasing rate, Γ_ϕ . Both the accumulated transfer efficiency, η_Q , and the time-averaged l_1 -coherence, $\bar{C}$, decreased as environmental dephasing increased, but they did so on substantially different scales.

In the absence of pure dephasing, the calculated transfer efficiency was

$$\eta_Q = 0.8168,$$

while the corresponding time-averaged coherence was

$$\bar{C} = 0.1026.$$

At $\Gamma_\phi/J = 0.10$, the transfer efficiency remained 0.6328, whereas the time-averaged coherence had decreased to 0.0600.

Increasing the dephasing to $\Gamma_\phi/J = 0.20$ reduced $\bar{C}$ further to 0.0405, while more than half of the initially transferred excitation remained represented by $\eta_Q = 0.5136$. The difference became progressively more pronounced at stronger dephasing. At $\Gamma_\phi/J = 0.50$, the calculated transfer efficiency remained 0.3301, whereas the time-averaged coherence had fallen to 0.0189. The calculated transfer efficiencies and time-averaged coherence values over the dephasing range examined are summarised in Table 2

Table 2. Calculated transfer efficiency and time-averaged coherence as functions of pure dephasing

Γ_ϕ/J	Transfer efficiency, η_Q	Time-averaged coherence, $\bar{C}$
0.00	0.8168	0.1026
0.10	0.6328	0.0600
0.20	0.5136	0.0405
0.50	0.3301	0.0189
1.00	0.2148	0.0095
2.00	0.1363	0.0049
5.00	0.0641	0.0021

The different rates of decay of transfer efficiency and time-averaged coherence with increasing dephasing are shown in Figure 2.

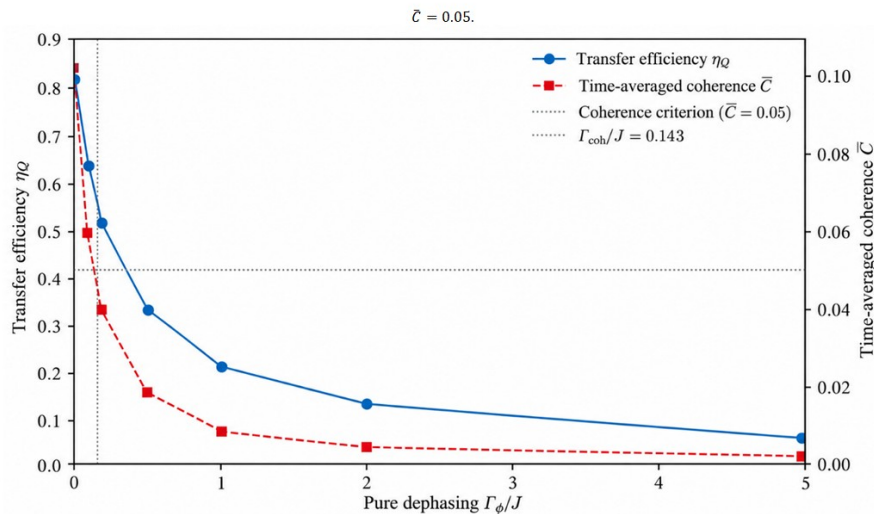


Figure 2. Dephasing dependence of quantum transfer efficiency and time-averaged coherence

Calculated transfer efficiency, η_Q , and time-averaged coherence, $\bar{C}$, are shown as functions of the dimensionless pure-dephasing strength, Γ_ϕ/J . The coherence measure decreases substantially more rapidly with increasing dephasing than the transfer efficiency. The horizontal dotted line denotes the adopted operational coherence criterion, $\bar{C} = 0.05$, while the vertical dotted line marks the corresponding coherence-loss threshold, $\Gamma_{coh}/J \approx 0.1431$. Substantial excitation transfer therefore persists after the selected coherence measure has crossed its operational threshold.

Interpolation of the finer numerical dephasing sweep gives

$$\Gamma_{coh} = 0.1431J. \quad (19)$$

At this point, the transfer efficiency remains approximately

$$\eta_Q = 0.5754.$$

Thus, the selected coherence measure reaches its operational threshold while substantial population transfer through the molecular network is still present.

Resonance enhancement persists at substantially stronger dephasing: The persistence of resonance was examined by comparing the resonant configuration with an off-resonant reference in which the bridge and acceptor detunings were set to

$$\Delta_B/J = \Delta_A/J = 2,$$

while all other parameters were held fixed.

The resonance-enhancement factor R_Q decreased continuously as environmental dephasing increased. At low dephasing, the difference between resonant and off-resonant transfer was particularly large because the detuned network transferred only a small fraction of the excitation reaching the acceptor channel.

At

$$\Gamma_\phi/J = 0.50,$$

the calculated resonance-enhancement factor was

$$R_Q = 1.3077,$$

corresponding to approximately 131% greater transfer than in the detuned reference configuration.

At

$$\Gamma_\phi/J = 1.00,$$

resonance continued to provide an enhancement of

$$R_Q = 0.2690,$$

or approximately 27%.

The enhancement subsequently approached the predefined 5% survival criterion. At

$$\Gamma_\phi/J = 1.50,$$

the calculated value was

$$R_Q = 0.0559,$$

whereas at

$$\Gamma_\phi/J = 1.55$$

it had decreased to

$$R_Q = 0.0461.$$

Numerical interpolation of the crossing point $R_Q = 0.05$ gives the resonance-survival threshold

$$\Gamma_{\text{res}} = 1.5294J. \quad (20)$$

The corresponding resonant transfer efficiency at this threshold is approximately

$$\eta_Q = 0.1630.$$

Resonance enhancement therefore persists to a dephasing strength more than an order of magnitude greater than that associated with the selected coherence threshold.

3.3 Resonance-coherence separation regime

The independently obtained coherence and resonance thresholds are

$$\Gamma_{\text{coh}} = 0.1431J$$

and

$$\Gamma_{\text{res}} = 1.5294J.$$

Their difference gives

$$\Delta\Gamma_{\text{RC}} = \Gamma_{\text{res}} - \Gamma_{\text{coh}} = 1.3863J. \quad (21)$$

The model therefore exhibits a finite interval

$$0.1431 < \frac{\Gamma_\phi}{J} < 1.5294 \quad (22)$$

within which the time-averaged coherence lies below the selected operational threshold while resonance continues to provide more than a 5% enhancement of molecular energy transfer.

This interval constitutes the resonance-coherence separation regime introduced in the present work. The three dynamical regimes defined by the two operational thresholds are summarised in Table 3.

Table 3. Dynamical regimes obtained from the baseline numerical model

Regime	Dephasing range	Principal behaviour
Coherence-retaining regime	$\Gamma_\phi/J < 0.1431$	Coherence and resonance enhancement both exceed the operational thresholds
Resonance-coherence separation regime	$0.1431 < \Gamma_\phi/J < 1.5294$	Coherence is below its threshold while resonance enhancement remains above 5%
Strongly dephased regime	$\Gamma_\phi/J > 1.5294$	Both coherence and resonance enhancement are below their respective thresholds

The numerical separation between the two characteristic scales is substantial:

$$\frac{\Gamma_{\text{res}}}{\Gamma_{\text{coh}}} \approx 10.69. \quad (23)$$

The resulting resonance-coherence separation regime and its two bounding thresholds are illustrated in Figure 3.

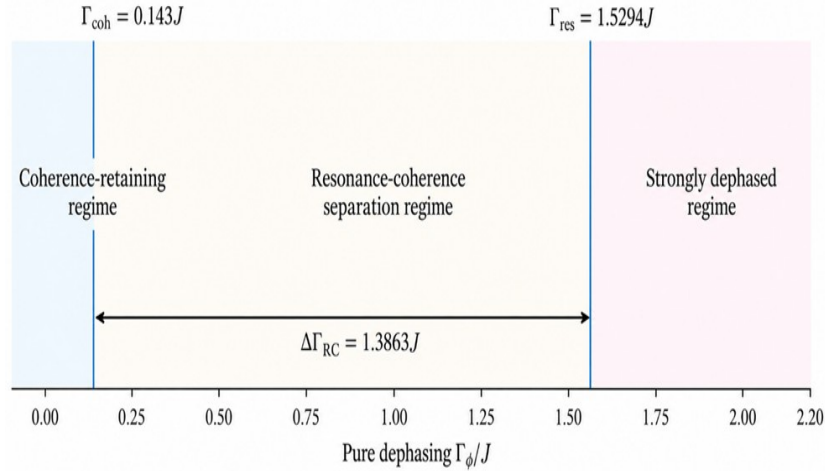


Figure 3. Operational resonance-coherence separation regime

The coherence-loss threshold, $\Gamma_{\text{coh}} \approx 0.1431J$, and resonance-survival threshold, $\Gamma_{\text{res}} \approx 1.5294J$, divide the dephasing axis into three operational regimes. For $\Gamma_{\phi} < \Gamma_{\text{coh}}$, both coherence and resonance enhancement remain above their adopted thresholds. For $\Gamma_{\text{coh}} < \Gamma_{\phi} < \Gamma_{\text{res}}$, the system lies in the resonance-coherence separation regime, in which the selected coherence measure has fallen below its threshold while resonance enhancement remains above its criterion. For $\Gamma_{\phi} > \Gamma_{\text{res}}$, both quantities are below their respective operational thresholds. The resulting separation width is $\Delta\Gamma_{\text{RC}} \approx 1.3863J$.

Thus, according to the operational definitions adopted here, the resonant-transfer signature survives to a dephasing strength approximately 10.7 times the coherence threshold.

Evolution of the resonance advantage: The behaviour of the resonant and detuned systems also reveals that the disappearance of resonance enhancement is gradual rather than abrupt. At $\Gamma_{\phi}/J = 0.50$, the resonant transfer efficiency is 0.3301, compared with 0.1430 for the detuned system. At $\Gamma_{\phi}/J = 1.00$, the corresponding values are 0.2148 and 0.1693, respectively.

By $\Gamma_{\phi}/J = 1.50$, the calculated efficiencies have approached one another, with

$$\eta_Q^{(\text{res})} = 0.1651$$

and

$$\eta_Q^{(\text{off})} = 0.1563.$$

At still stronger dephasing, the resonant advantage disappears. For example, at $\Gamma_{\phi}/J = 2.00$, the calculated resonance-enhancement factor is slightly negative,

$$R_Q = -0.0041,$$

indicating that the resonant and detuned responses have become effectively equivalent within the scale of the model.

This convergence is consistent with environmental broadening progressively erasing the energetic selectivity that initially favours the resonant configuration.

Separation between coherence loss and resonance loss: The principal result is illustrated by comparing the decay of $\bar{C}$ with that of R_Q . The coherence measure falls rapidly with increasing dephasing and crosses its operational threshold near $\Gamma_{\phi}/J = 0.143$. Resonance enhancement, by contrast, remains substantial throughout a much wider interval and does not cross its corresponding 5% criterion until $\Gamma_{\phi}/J \approx 1.529$. These distinct scales show that the disappearance of coherence and the disappearance of resonance-mediated enhancement are not simultaneous within the present model. This behaviour is physically consistent with the different roles of phase coherence and population redistribution. Pure dephasing directly suppresses the off-diagonal density-matrix elements entering C_{l_1} , whereas excitation populations can continue to redistribute through the coupled molecular network after those coherence terms have become small. Previous studies have similarly demonstrated that environmental interactions may

reduce coherence without immediately eliminating efficient excitation transport (38,39). The present calculation addresses a narrower question by explicitly resolving the environmental scales associated with the two effects. The positive value

$$\Delta\Gamma_{\text{RC}} = 1.3863J$$

shows that resonance-dependent transport remains distinguishable over a broad interval after the selected coherence measure has crossed its operational threshold.

Sensitivity of the result to the operational threshold: The absolute values of Γ_{coh} and Γ_{res} depend on the operational criteria used to define them. The operational criteria adopted here are therefore not interpreted as fundamental quantum-mechanical constants.

The physically relevant result is instead the separation of the two decay scales. The coherence curve decreases substantially earlier than the resonance-enhancement curve, producing a broad intermediate region rather than two nearly coincident crossings.

Consequently, the principal conclusion does not depend on interpreting either threshold as a sharp phase transition. The quantities Γ_{coh} and Γ_{res} are operational markers that make the relative persistence of coherence and resonance quantitatively comparable.

Principal numerical finding

For the baseline model,

$$\Gamma_{\text{coh}} = 0.1431J,$$

$$\Gamma_{\text{res}} = 1.5294J,$$

and

$$\Delta\Gamma_{\text{RC}} = 1.3863J. \quad (24)$$

The numerical simulations therefore support the existence of a finite resonance-coherence separation regime within the present open quantum-system model. The central result can be stated succinctly: resonance-enhanced molecular energy transfer persists substantially beyond the dephasing scale at which the selected coherence measure has fallen below its operational threshold. This distinction provides the basis for the Discussion that follows.

DISCUSSION

The numerical analysis reveals a clear separation between the environmental scale governing loss of the selected coherence-sensitive response and the scale governing loss of resonance-enhanced molecular energy transfer. For the baseline model, the time-averaged coherence crosses its operational threshold at

$$\Gamma_{\text{coh}} = 0.1431J,$$

whereas the resonance-enhancement factor remains above its corresponding 5% criterion until

$$\Gamma_{\text{res}} = 1.5294J.$$

The resulting resonance-coherence separation width is

$$\Delta\Gamma_{\text{RC}} = 1.3863J$$

Thus, the resonance-survival scale is approximately 10.7 times the coherence threshold under the baseline conditions. This separation indicates that the two observables probe different aspects of the molecular dynamics. Pure dephasing acts directly on off-diagonal density-matrix elements and therefore suppresses phase information comparatively rapidly. Population redistribution and resonance-dependent transfer can nevertheless remain observable after the coherence measure has become small. Environmental coupling can therefore weaken quantum coherence without immediately eliminating the functional consequences of energetic resonance.

Resonance enhancement is not sufficient evidence of quantum coherence: One implication is that an experimentally observed resonant enhancement should not, by itself, be interpreted as evidence that a molecular transport process remains quantum coherent. Classical coupled systems can exhibit resonance, and quantum networks subjected to dephasing may retain enhanced population transfer even when phase-sensitive observables have substantially decayed. This distinction is consistent with theoretical work demonstrating that dephasing can improve transport under particular conditions (40,41). It also supports the broader view that the functional efficiency of a molecular network and the degree of quantum coherence present within that network are related but fundamentally different quantities (9). Accordingly, evidence for a quantum contribution should ideally involve observables that are sensitive to phase information or that cannot be reproduced by a suitably constructed classical

benchmark. Population transfer alone provides information about the outcome of the dynamics, but not necessarily about the microscopic nature of the trajectory leading to that outcome.

Meaning of the resonance-coherence separation regime: The resonance-coherence separation regime introduced here should not be interpreted as a sharply defined new phase of matter or as a universal quantum-classical boundary. It is an operational dynamical regime defined within the present model by independently specified thresholds. Its physical significance is more limited but potentially useful. It identifies conditions under which resonance remains functionally relevant even though a selected coherence-sensitive observable has fallen below a prescribed distinguishability criterion. The width of this regime,

$$\Delta\Gamma_{RC},$$

therefore depends on the operational thresholds adopted in the present analysis. Its absolute numerical value is consequently model dependent. The more important result is the existence, for the baseline model, of a non-zero interval,

$$\Delta\Gamma_{RC} > 0.$$

This demonstrates that, under the adopted operational criteria, resonance survival and coherence survival occur at distinct dephasing scales.

Role of the matched classical benchmark: A classical dissipative network is included as a reference framework for subsequent direct comparison with the quantum dynamics. This is important because the presence of non-zero off-diagonal density-matrix elements does not automatically mean that experimentally measured populations will exhibit behaviour distinguishable from classical dynamics. The discrepancy measure $\mathcal{D}_{QC}$ is introduced as a formal basis for future direct comparison of the time-dependent quantum and classical acceptor responses. Such a trajectory-level comparison could provide a more operational interpretation of the quantum-to-classical crossover. The relevant experimental question is not necessarily whether

$$C_{l_1} = 0,$$

but whether the remaining coherence generates an observable response distinguishable from an appropriate non-quantum reference. Recent work has similarly emphasised the need to identify quantum signatures in excitation transfer rather than assuming that optimal transport is itself evidence of quantumness (9). The present model adopts that philosophy but applies it specifically to the separation between resonance persistence and coherence-sensitive distinguishability.

Dependence on environmental coupling: The transition is expected to depend strongly on the structure of the molecular environment. The baseline calculation uses a Markovian pure-dephasing model because it provides a transparent first test of the proposed separation. Real molecular environments may exhibit structured spectral densities, correlated fluctuations and memory effects (12,13). Such effects could modify both threshold values. Non-Markovian dynamics may temporarily restore coherence, alter energy-flow pathways or shift the effective timescale over which the classical and quantum trajectories become similar. Similarly, site-dependent dephasing may produce localised regions of coherence even when the network-averaged coherence is small. The present results should therefore be interpreted as demonstrating the principle of threshold separation within a controlled minimal model rather than establishing universal numerical values for molecular systems.

Experimental implications: The framework suggests a simple experimental strategy. A molecular or excitonic system could be characterised while an environmental control variable, such as temperature, solvent environment, static disorder or externally introduced noise, is systematically varied. At each condition, two classes of measurements would be required. The first would quantify resonance-dependent transport, for example through transfer yield, acceptor population or frequency-resolved response. The second would probe coherence-sensitive dynamics using phase-resolved or ultrafast spectroscopic observables. Modern ultrafast measurements increasingly provide access to molecular coherence on relevant timescales (23,24). If resonance enhancement remained measurable after coherence-sensitive features had fallen below experimental resolution, the system would exhibit the experimental analogue of the resonance-coherence separation regime proposed here. The experimentally relevant thresholds would then be determined by measurement sensitivity rather than by an arbitrary universal percentage. This is why the operational criteria used in the baseline calculations should be regarded as analysis choices rather than universal physical thresholds.

Limitations

Several limitations should be noted. First, the donor-bridge-acceptor network is intentionally minimal and does not capture the structural complexity of realistic molecular aggregates. Second, the baseline environment is Markovian and does not explicitly include structured vibrational spectral densities. Third, the classical comparator is designed to reproduce the dominant resonance architecture rather than every possible classical stochastic representation of the quantum model. The present calculations also operate within a weak-driving, single-excitation approximation. Strong-field excitation, multiphoton processes, anharmonic vibrational effects and many-body excitonic interactions are outside the current scope. Finally, the operational thresholds used to extract Γ_{coh} and Γ_{res} are analysis choices rather than fundamental constants. Future work should test whether the separation regime remains present when the operational thresholds and other model parameters are varied over reasonable ranges. Despite these limitations, the minimal model is useful precisely because it isolates the central question without requiring molecule-specific

fitting. It provides a direct test of whether the disappearance of coherence-sensitive behaviour must coincide with the disappearance of resonance-enhanced transport.

Significance of the framework: The principal contribution of the present work is not the established observation that dephasing suppresses quantum coherence, nor the established fact that resonance can enhance molecular energy transfer. The contribution lies in treating the disappearance of coherence-sensitive behaviour and the disappearance of resonance enhancement as two independently quantifiable dynamical events within the same model.

For the baseline network, these events occur at substantially different environmental scales, producing

$$\Delta\Gamma_{\text{RC}} = 1.3863J.$$

The resulting intermediate regime demonstrates that resonance-enhanced transfer can persist after the selected coherence measure has crossed its operational threshold. This distinction separates two different questions: whether resonance continues to enhance molecular transport, and whether the selected coherence-sensitive measure remains above its operational threshold. The present results show that these two operational thresholds occur at substantially different dephasing strengths. The quantity $\Delta\Gamma_{\text{RC}}$ therefore provides a compact way of quantifying the separation between resonance survival and coherence survival. Its absolute value remains model dependent, but its existence provides a testable feature that can be examined in more realistic molecular networks and experimentally parameterised systems.

CONCLUSION

This study develops a compact open quantum-system framework for examining whether the environmental scale governing loss of the selected coherence-sensitive response is necessarily the same as the scale governing loss of resonance-enhanced molecular energy transfer. A minimal donor-bridge-acceptor network was analysed under increasing pure dephasing, with coherence and resonance enhancement treated as independent dynamical observables rather than using transfer efficiency alone to characterise the underlying dynamics.

The numerical calculations identify two distinct operational scales in the baseline model. The time-averaged coherence criterion is reached at

$$\Gamma_{\text{coh}} = 0.1431J,$$

whereas resonance enhancement remains above the selected 5% criterion until

$$\Gamma_{\text{res}} = 1.5294J.$$

The resulting resonance-coherence separation width is

$$\Delta\Gamma_{\text{RC}} = \Gamma_{\text{res}} - \Gamma_{\text{coh}} = 1.3863J. \quad (26)$$

Thus, under the baseline conditions, the resonance-survival scale is approximately 10.7 times the corresponding coherence threshold. The principal physical implication is that resonance-enhanced molecular energy transfer can remain observable after the selected measure of quantum coherence has already fallen below its operational threshold. Resonance survival and coherence survival are therefore not interchangeable descriptions of the same dynamical transition. Population redistribution through a coupled molecular network can remain sensitive to energetic matching even when environmental dephasing has substantially reduced phase-sensitive information. This distinction is important for the interpretation of molecular transport experiments. Observation of enhanced transfer near resonance should not, by itself, be taken as evidence that the underlying dynamics remain strongly quantum coherent. Establishing a quantum-coherent contribution requires additional observables that are sensitive to phase information or that distinguish the measured dynamics from an appropriate classical or incoherent benchmark. The quantity $\Delta\Gamma_{\text{RC}}$ provides a simple operational measure of the separation between these two effects. Its numerical value is model dependent and should not be regarded as a universal constant. The more general result is the existence, within the present model, of a finite intermediate regime in which resonance-mediated transport remains significant after coherence has been strongly suppressed. The framework is deliberately species-independent and is intended as a controlled theoretical model rather than a microscopic description of a particular molecular system. Future extensions should examine whether the resonance-coherence separation persists in larger networks, structured spectral environments, non-Markovian dynamics, energetic disorder and experimentally parameterised excitonic or vibrational systems. Future work should also include direct matched-classical trajectory analysis to determine when the quantum and classical transfer dynamics become operationally indistinguishable. Overall, the present results support a clear separation between the persistence of molecular resonance and the persistence of the selected coherence-sensitive response. This provides a quantitative basis for distinguishing resonance-enhanced energy transfer from the survival of quantum coherence under increasing environmental dephasing.

Data Availability Statement: No experimental or externally acquired dataset was used in this theoretical study. All numerical data reported in the manuscript were generated from the mathematical model, equations and parameter values specified. The

numerical datasets underlying the reported tables and figures will be retained with the computational records of the study and made available by the corresponding author upon reasonable request.

Code Availability Statement: The computational implementation used for numerical integration of the open quantum-system equations and generation of the reported results, together with the parameter definitions required to reproduce the calculations, will be made available by the corresponding author upon reasonable request.

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REFERENCES

1. Jha, A., Zheng, F., Liu, Z., Mukamel, S., Thorwart, M., Miller, R. J. D. & Duan, H.-G. Quantum coherent dynamics in photosynthetic protein complexes. *Chemical Society Reviews* 55, 1089–1130 (2026). <https://doi.org/10.1039/D5CS00948K>.
2. Strich, R., Faraji, S. & Palacino-González, E. Extending quantum coherence lifetimes in nonadiabatic dissipative molecular systems with chirped pulses. *Physical Chemistry Chemical Physics* 27, 18525–18538 (2025). <https://doi.org/10.1039/D5CP01684C>.
3. Li, J., Shi, Y., Cui, C., Li, Y., Ruan, C. & Cheng, T. Unveiling quantum coherence effects in modulating electron transfer in platinum(II) donor-acceptor-donor systems. *Chemistry – A European Journal* 31, e202404512 (2025). <https://doi.org/10.1002/chem.202404512>.
4. Krupp, N., Groenhof, G. & Vendrell, O. Quantum dynamics simulation of exciton-polariton transport. *Nature Communications* 16, 5431 (2025). <https://doi.org/10.1038/s41467-025-61298-9>.
5. Delgado-Granados, L. H., Krogmeier, T. J., Sager-Smith, L. M., Avdic, I., Hu, Z., Sajjan, M., Abbasi, M., Smart, S. E., Narang, P., Kais, S., Schlingens, A. W., Head-Marsden, K. & Mazziotti, D. A. Quantum algorithms and applications for open quantum systems. *Chemical Reviews* 125, 1823–1839 (2025). <https://doi.org/10.1021/acs.chemrev.4c00428>.
6. Korol, R., Chen, X. & Franco, I. High-frequency tails in spectral densities. *The Journal of Physical Chemistry A* 129, 3587–3596 (2025). <https://doi.org/10.1021/acs.jpca.5c00943>.
7. Gustin, I., Chen, X. & Franco, I. Decoherence dynamics in molecular qubits: Exponential, Gaussian and beyond. *The Journal of Chemical Physics* 162, 064106 (2025). <https://doi.org/10.1063/5.0246970>.
8. Song, Y., Qin, C., Dong, S., Li, X. & Wei, A. Quantum coherence effect in the interaction of light and molecules. *Laser & Photonics Reviews* 18, 2400093 (2024). <https://doi.org/10.1002/lpor.202400093>.
9. Peter, J. S., Holzinger, R., Ostermann, S. & Yelin, S. F. Examining the quantum signatures of optimal excitation energy transfer. *Physical Review Research* 6, 033252 (2024). <https://doi.org/10.1103/PhysRevResearch.6.033252>.
10. Zhu, R., Li, W., Zhen, Z., Zou, J., Liao, G., Wang, J., Wang, Z., Chen, H., Qin, S. & Weng, Y. Quantum phase synchronization via exciton-vibrational energy dissipation sustains long-lived coherence in photosynthetic antennas. *Nature Communications* 15, 3171 (2024). <https://doi.org/10.1038/s41467-024-47560-6>.
11. Jaiswal, V. K., Aranda Ruiz, D., Petropoulos, V., Kabaciński, P., Montorsi, F., Uboldi, L., Ugolini, S., Mukamel, S., Cerullo, G., Garavelli, M., Santoro, F. & Nenov, A. Sub-100-fs energy transfer in coenzyme NADH is a coherent process assisted by a charge-transfer state. *Nature Communications* 15, 4900 (2024). <https://doi.org/10.1038/s41467-024-48871-4>.
12. Kim, C. W. & Franco, I. General framework for quantifying dissipation pathways in open quantum systems. I. Theoretical formulation. *The Journal of Chemical Physics* 160, 214111 (2024). <https://doi.org/10.1063/5.0202860>.
13. Kim, C. W. & Franco, I. General framework for quantifying dissipation pathways in open quantum systems. II. Numerical validation and the role of non-Markovianity. *The Journal of Chemical Physics* 160, 214112 (2024). <https://doi.org/10.1063/5.0202862>.
14. Humphries, B. S., Kinslow, J. C., Green, D. & Jones, G. A. Role of quantum information in HEOM trajectories. *Journal of Chemical Theory and Computation* 20, 5383–5395 (2024). <https://doi.org/10.1021/acs.jctc.4c00144>.
15. Bose, A. Incorporation of empirical gain and loss mechanisms in open quantum systems through path integral Lindblad dynamics. *The Journal of Physical Chemistry Letters* 15, 3363–3368 (2024). <https://doi.org/10.1021/acs.jpclett.4c00489>.
16. Dutta, R. & Bagchi, B. Memory effects in the efficiency control of energy transfer under incoherent light excitation in noisy environments. *The Journal of Chemical Physics* 160, 245101 (2024). <https://doi.org/10.1063/5.0209909>.
17. Coane, C. V., Romanelli, M., Dall'Osto, G., Di Felice, R. & Corni, S. Unraveling the mechanism of tip-enhanced molecular energy transfer. *Communications Chemistry* 7, 32 (2024). <https://doi.org/10.1038/s42004-024-01118-1>.
18. Xiang, B. & Xiong, W. Molecular polaritons for chemistry, photonics and quantum technologies. *Chemical Reviews* 124, 2512–2552 (2024). <https://doi.org/10.1021/acs.chemrev.3c00662>.
19. Liu, Z. & Hanna, G. Population and energy transfer dynamics in an open excitonic quantum battery. *Molecules* 29, 889 (2024). <https://doi.org/10.3390/molecules29040889>.

20. Holzinger, R., Bassler, N. S., Ritsch, H. & Genes, C. Scaling law for Kasha's rule in photoexcited molecular aggregates. *The Journal of Physical Chemistry A* 128, 3910–3915 (2024). <https://doi.org/10.1021/acs.jpca.4c00342>.
21. Stojanovic, L., Giannini, S. & Blumberger, J. Exciton transport in the nonfullerene acceptor O-IDTBR from nonadiabatic molecular dynamics. *Journal of Chemical Theory and Computation* 20, 6241–6252 (2024). <https://doi.org/10.1021/acs.jctc.4c00605>.
22. Cui, X., Yan, Y. & Wei, J. Theoretical study on the excitation energy transfer dynamics in the phycoerythrin PE555 light-harvesting complex. *ACS Omega* 9, 51228–51236 (2024). <https://doi.org/10.1021/acsomega.4c07445>.
23. Tang, Z., Jarupula, R. & Yong, H. Pushing the limits of ultrafast diffraction: Imaging quantum coherences in isolated molecules. *iScience* 27, 110705 (2024). <https://doi.org/10.1016/j.isci.2024.110705>.
24. Gustin, I., Kim, C. W., McCamant, D. W. & Franco, I. Mapping electronic decoherence pathways in molecules. *Proceedings of the National Academy of Sciences of the United States of America* 120, e2309987120 (2023). <https://doi.org/10.1073/pnas.2309987120>.
25. Cao, J., Cogdell, R. J., Coker, D. F., Duan, H.-G., Hauer, J., Kleinekathöfer, U., Jansen, T. L. C., Mančal, T., Miller, R. J. D., Ogilvie, J. P., Prokhorenko, V. I., Renger, T., Tan, H.-S., Tempelaar, R., Thorwart, M., Thyryhaug, E., Westenhoff, S. & Zigmantas, D. Quantum biology revisited. *Science Advances* 6, eaaz4888 (2020). <https://doi.org/10.1126/sciadv.aaz4888>.
26. Manzano, D. A short introduction to the Lindblad master equation. *AIP Advances* 10, 025106 (2020). <https://doi.org/10.1063/1.5115323>.
27. Streltsov, A., Adesso, G. & Plenio, M. B. Colloquium: Quantum coherence as a resource. *Reviews of Modern Physics* 89, 041003 (2017). <https://doi.org/10.1103/RevModPhys.89.041003>.
28. Baumgratz, T., Cramer, M. & Plenio, M. B. Quantifying coherence. *Physical Review Letters* 113, 140401 (2014). <https://doi.org/10.1103/PhysRevLett.113.140401>.
29. Hildner, R., Brinks, D., Nieder, J. B., Cogdell, R. J. & van Hulst, N. F. Quantum coherent energy transfer over varying pathways in single light-harvesting complexes. *Science* 340, 1448–1451 (2013). <https://doi.org/10.1126/science.1235820>.
30. Collini, E. Spectroscopic signatures of quantum-coherent energy transfer. *Chemical Society Reviews* 42, 4932–4947 (2013). <https://doi.org/10.1039/C3CS35444J>.
31. Chin, A. W., Huelga, S. F. & Plenio, M. B. Coherence and decoherence in biological systems: Principles of noise-assisted transport and the origin of long-lived coherences. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 370, 3638–3657 (2012). <https://doi.org/10.1098/rsta.2011.0224>.
32. Panitchayangkoon, G., Hayes, D., Fransted, K. A., Caram, J. R., Harel, E., Wen, J., Blankenship, R. E. & Engel, G. S. Long-lived quantum coherence in photosynthetic complexes at physiological temperature. *Proceedings of the National Academy of Sciences of the United States of America* 107, 12766–12770 (2010). <https://doi.org/10.1073/pnas.1005484107>.
33. Collini, E., Wong, C. Y., Wilk, K. E., Curmi, P. M. G., Brumer, P. & Scholes, G. D. Coherently wired light-harvesting in photosynthetic marine algae at ambient temperature. *Nature* 463, 644–647 (2010). <https://doi.org/10.1038/nature08811>.
34. Sarovar, M., Ishizaki, A., Fleming, G. R. & Whaley, K. B. Quantum entanglement in photosynthetic light-harvesting complexes. *Nature Physics* 6, 462–467 (2010). <https://doi.org/10.1038/nphys1652>.
35. Ishizaki, A. & Fleming, G. R. Theoretical examination of quantum coherence in a photosynthetic system at physiological temperature. *Proceedings of the National Academy of Sciences of the United States of America* 106, 17255–17260 (2009). <https://doi.org/10.1073/pnas.0908989106>.
36. Ishizaki, A. & Fleming, G. R. Unified treatment of quantum coherent and incoherent hopping dynamics in electronic energy transfer: Reduced hierarchy equation approach. *The Journal of Chemical Physics* 130, 234111 (2009). <https://doi.org/10.1063/1.3155372>.
37. Nazir, A. Correlation-dependent coherent to incoherent transitions in resonant energy transfer dynamics. *Physical Review Letters* 103, 146404 (2009). <https://doi.org/10.1103/PhysRevLett.103.146404>.
38. Caruso, F., Chin, A. W., Datta, A., Huelga, S. F. & Plenio, M. B. Highly efficient energy excitation transfer in light-harvesting complexes: The fundamental role of noise-assisted transport. *The Journal of Chemical Physics* 131, 105106 (2009). <https://doi.org/10.1063/1.3223548>.
39. Rebentrost, P., Mohseni, M., Kassal, I., Lloyd, S. & Aspuru-Guzik, A. Environment-assisted quantum transport. *New Journal of Physics* 11, 033003 (2009). <https://doi.org/10.1088/1367-2630/11/3/033003>.
40. Plenio, M. B. & Huelga, S. F. Dephasing-assisted transport: Quantum networks and biomolecules. *New Journal of Physics* 10, 113019 (2008). <https://doi.org/10.1088/1367-2630/10/11/113019>.
41. Mohseni, M., Rebentrost, P., Lloyd, S. & Aspuru-Guzik, A. Environment-assisted quantum walks in photosynthetic energy transfer. *The Journal of Chemical Physics* 129, 174106 (2008). <https://doi.org/10.1063/1.3002335>.
42. Jang, S., Cheng, Y.-C., Reichman, D. R. & Eaves, J. D. Theory of coherent resonance energy transfer. *The Journal of Chemical Physics* 129, 101104 (2008). <https://doi.org/10.1063/1.2977974>.
43. Engel, G. S., Calhoun, T. R., Read, E. L., Ahn, T.-K., Mančal, T., Cheng, Y.-C., Blankenship, R. E. & Fleming, G. R. Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems. *Nature* 446, 782–786 (2007). <https://doi.org/10.1038/nature05678>.
44. Lindblad, G. On the generators of quantum dynamical semigroups. *Communications in Mathematical Physics* 48, 119–130 (1976). <https://doi.org/10.1007/BF01608499>.
45. Gorini, V., Kossakowski, A. & Sudarshan, E. C. G. Completely positive dynamical semigroups of N-level systems. *Journal of Mathematical Physics* 17, 821–825 (1976). <https://doi.org/10.1063/1.522979>