

Quantum biology, quantum simulation and quantum coherent devices

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Received May 7, 2026; accepted July 7, 2026; published online September 24, 2026

Quantum effects have been proposed to play functional roles in biological processes such as photosynthetic energy transfer and avian magnetoreception. In photosynthetic light-harvesting complexes, excitation energy transfer can proceed with remarkably high efficiency. With advances in experimental techniques, two-dimensional electronic spectroscopy can reveal dynamic processes such as coherence and coupling within a system, and it plays an important role in studying energy transfer in photosynthesis. On the theory side, methods such as the generalized Bloch-Redfield theory and the hierarchical equations of motion are used to model photosynthetic systems. Quantum simulation has also emerged as a complementary route for investigating photosynthetic dynamics, with implementations on multiple experimental platforms. In recent years, a series of studies has introduced quantum coherence into artificial systems to enhance energy transfer efficiency, laying the groundwork for the design of coherent devices with efficient energy transport. Birds are thought to sense direction by exploiting the weak geomagnetic field through spin-dependent chemical reactions. Theoretical frameworks for animal navigation include magnetite-based mechanisms, magnetoreceptor genes, and the radical-pair mechanism. Quantum simulation of magnetoreception-related spin dynamics has likewise progressed across multiple platforms. Inspired by animal navigation, diverse quantum effects have been applied to improve sensing and to support navigation tasks. This review summarizes recent progress in quantum coherence related to photosynthesis and avian magnetoreception, with emphasis on experimental advances, theoretical methods, quantum simulation, and the design of bioinspired coherent devices.

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Citation: R.-H. Chen, J. Dong, W. Yang, Q. Ai, and G.-L. Long, Quantum biology, quantum simulation and quantum coherent devices, *Sci. China-Phys. Mech. Astron.* **69**, 110301 (2026), <https://doi.org/10.1007/s11433-026-3070-9>

1 Introduction

Quantum coherence, once thought to be too fragile to survive in complex and warm biological environments, is now

increasingly recognized as a potentially important ingredient in several biological functions, most notably in photosynthetic energy transfer and magnetoreception-based animal navigation [1, 2]. These discoveries have stimulated intense interest at the interface of quantum physics, chemistry, and biology, not only because they deepen our understand-

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ing of living systems, but also because they offer new design principles for artificial quantum devices.

Photosynthesis is a highly coordinated biochemical process that converts solar energy into chemical energy. It is well known that the process of photosynthesis mainly includes four aspects, namely the primary reaction, electron transfer, photophosphorylation, and carbon dioxide fixation [3]. Among these stages, exciton energy transfer (EET) in light-harvesting complexes has attracted particular attention because it proceeds with remarkably high efficiency. However, the processes of energy and electron transfer are ultrafast and occur on the order of 1 ps. The excitation energy is transferred to the reaction center on a timescale of 30 ps, and the subsequent electron transfer is completed in about 3 ps. Since energy transfer in photosynthesis can be regarded as an open-system dynamics, several theoretical approaches have been developed [4–10], including Förster theory [4, 5, 11, 12], modified Redfield theory [6, 7, 13–16], and the hierarchical equations of motion (HEOM) [10, 17, 18]. While these methods have significantly advanced our understanding of photosynthetic dynamics, they are often based on specific approximations or become computationally demanding in realistic parameter regimes.

Progress in ultrafast spectroscopy has provided a powerful experimental window into these dynamics. In particular, two-dimensional electronic spectroscopy (2DES) has enabled the direct characterization of coupling patterns, energy-transfer pathways, and coherent signatures in pigment-protein complexes. In the late 1980s, the molecular structure of the purple bacterial reaction center protein complex was obtained [19], and subsequently, several other molecular structures of reaction centers and light-harvesting antenna protein complexes were widely determined [20–23]. In 2005 [24], 2DES was used to study the energy transfer pathways in the Fenna-Matthews-Olson (FMO) photosynthetic complex. At the same time, Read et al. [25] used 2DES to study the energy transfer process in the FMO photosynthetic complex of green sulfur bacteria, revealing the key role of quantum coherence in efficient energy transfer during photosynthesis. Since then, the extent to which quantum effects contribute functionally to photosynthesis has become a central topic of debate and exploration.

Another striking arena in quantum biology is animal navigation. Many migratory animals, especially birds, are believed to sense the Earth's weak geomagnetic field and use it as a directional cue. One of the most influential explanations for this ability is the radical-pair mechanism (RPM), according to which spin-dependent chemical reactions become sensitive to the geomagnetic field through singlet-triplet interconversion driven by hyperfine interactions and external magnetic fields. This mechanism is particularly intriguing

from a quantum perspective because it involves coherent spin dynamics, and in some models even transient quantum entanglement between the two radicals [26–28]. Remarkably, such quantum correlations have been predicted to persist for biologically relevant times under ambient conditions, challenging the conventional view that nontrivial quantum effects cannot survive in noisy environments. The magnetically sensitive reaction dynamics in radical-pair systems can also be described using generalized Holstein-type models that explicitly include spin degrees of freedom.

Despite substantial progress, understanding quantum effects in biological systems remains theoretically and computationally challenging. Most existing methods for photosynthetic energy transfer rely on approximations that are valid only in restricted parameter regimes, while numerically exact approaches often suffer from high computational cost. Similar challenges arise in modeling spin-dependent dynamics in magnetoreception. In this context, quantum simulation offers a promising complementary strategy. By exploiting quantum superposition and entanglement, quantum simulators can emulate complex many-body and open-system dynamics in ways that are difficult for classical computation. For this reason, quantum simulation has been proposed and implemented as a tool for studying both photosynthetic energy transfer and animal navigation [21, 22, 26, 29–38]. Recent years have witnessed experimental realizations of such simulations across multiple platforms, further strengthening the connection between quantum information science and quantum biology.

Beyond biological understanding, these studies have also inspired the development of bioinspired quantum technologies. Motivated by the possibility that coherence can improve energy transport and magnetic sensitivity, researchers have proposed both theoretical models and experimental architectures for quantum coherent devices. For example, Creatore et al. [39] introduced a simplified model in which two dipole-coupled pigments form bright and dark states that effectively replace the natural reaction center. In this design, light first excites the bright state, followed by rapid nonradiative transfer to the dark state, which then injects an electron into an artificial acceptor. This mechanism suppresses radiative losses and enhances charge injection, thereby increasing photocurrent and improving power output. In a related direction, Xiao et al. [40], inspired by animal magnetoreception, showed that local magnetic-field fluctuations generated by magnetic proteins can, under resonance and triplet nondegeneracy conditions, drive singlet-triplet interconversion in radical pairs and enhance directional sensitivity to the geomagnetic field. Their results suggest that magnetic noise, rather than being purely detrimental, can in some cases improve metrological performance. Recent studies have fur-

ther extended this idea from biological magnetoreception to controllable molecular spin devices. Chowdhury et al. [41] showed that a Pontryagin maximum principle-based strategy can steer coherent and incoherent dynamics in noisy spin-correlated radical pairs. Smith et al. [42] further showed that structured interrational motion in cryptochrome can enhance directional sensitivity and push radical pair magnetosensing precision toward the quantum Cramér Rao bound. These results suggest that molecular motion and environmental noise can serve as functional resources for bioinspired weak field sensing, rather than being only sources of decoherence.

This review is organized around three connected themes. We first discuss photosynthesis and avian magnetoreception as representative biological settings in which quantum effects may play functional roles. We then summarize quantum simulation approaches for modeling coherent energy-transfer and spin-dynamical processes. Finally, we discuss how these ideas can be translated into bioinspired coherent devices for efficient energy transport and weak-field sensing.

2 Quantum effects in photosynthesis

2.1 Theoretical studies of photosynthesis

The study of energy transfer in photosynthetic systems requires the application of quantum dissipative dynamics methods. In such investigations, the pigment molecules and other relevant structures of interest are typically treated as the system, while the remaining structures, such as the protein scaffolds, are treated as the environment. To date, various quantum dissipative dynamics methods have been proposed [4–10].

Theoretical approaches to studying photosynthesis include the Förster theory, which describes stochastic resonance energy transfer between weakly coupled pigment molecules

[4, 5, 11, 12]. The modified Redfield theory is more suitable for delocalized exciton states with relatively strong electronic coupling and weak off-diagonal exciton-bath coupling [6, 7, 13–16]. The generalized Bloch-Redfield theory characterizes non-Markovian open quantum systems [8, 9]. The HEOM enables highly accurate simulations of energy transfer between pigment molecules [10, 17, 18]. However, these theoretical methods all have their own ranges of applicability.

To make the differences among these theoretical methods clearer, Table 1 gives a brief comparison of Förster theory, modified Redfield theory, generalized Bloch-Redfield theory, and HEOM. These methods are useful in different physical regimes. Förster theory is mainly used when the electronic coupling is weak, and the excitation is relatively localized. Modified Redfield theory is more suitable for describing population relaxation between exciton states when excitonic coupling is strong. Generalized Bloch-Redfield theory can treat coherent evolution and relaxation within the framework of open quantum systems, and can be used for dynamics with memory effects. HEOM can describe coherent wave-like motion, incoherent hopping, and the intermediate EET regime in a unified way, but it usually requires a high computational cost. This comparison helps readers quickly understand the applicable range of each method and also explains why quantum simulation can serve as a useful complement for studying photosynthetic energy transfer. The detailed discussions can be found in the review by Tao et al. [43].

2.2 Two-dimensional electronic spectroscopy

2DES is an ultrafast nonlinear laser spectroscopy technique that provides higher temporal and spectral resolution than conventional linear spectroscopy [44, 45]. In photosynthesis research, it has been used to resolve coherent dynamics, electronic couplings, and energy-transfer pathways in pigment-protein complexes [24, 25, 46–50].

Table 1 Comparison of several theoretical methods for photosynthetic energy transfer

Method	Applicable range	Main advantages	Limitations
Förster theory	Weak interchromophore electronic coupling and localized donor and acceptor excitations	Provides a transparent rate-based picture of incoherent hopping energy transfer and is computationally inexpensive	Not suitable for strongly delocalized excitons or coherent exciton dynamics. Its accuracy also depends on the spectral-overlap model and coupling approximation
Modified Redfield theory	Delocalized exciton states with relatively strong electronic coupling and weak off-diagonal exciton-bath coupling in the exciton basis	Describes population relaxation among exciton states and includes bath reorganization and pure dephasing more accurately than standard Redfield theory	Less reliable in the weak electronic coupling limit, for strong system-bath coupling, or when exciton energy gaps are small
Generalized Bloch-Redfield theory	Weak system-bath coupling, with possible non-Markovian or non-secular extensions	Propagates the reduced density matrix and can describe coherent evolution, relaxation, and dephasing within one framework	Still relies on perturbative treatment of the system-bath interaction. Its accuracy can be sensitive to Markov, secular, and bath-model approximations
HEOM	Nonperturbative and non-Markovian open-system dynamics with structured environments, provided that the bath correlation functions and hierarchy are converged	Can describe coherent wave-like motion, incoherent hopping, and intermediate EET regimes within a unified framework	Usually requires high computational and memory cost, especially for large pigment aggregates, low temperatures, long bath memory, or complex spectral densities

Using noncollinear three-pulse photon-echo spectroscopy, researchers have successfully used 2DES to investigate energy-transfer pathways in the FMO complex. Brixner et al. [24] directly demonstrated the existence of two parallel energy-transfer routes, showing that energy flow in the FMO complex does not simply follow a downhill hopping mechanism. Instead, it is guided by the spatial distribution of excitonic wavefunctions, emphasizing the structural and functional complexity of energy transfer in photosynthetic systems.

Polarization-dependent 2DES has further advanced the understanding of excitonic structures and energy-transfer dynamics in the FMO complex of green sulfur bacteria. Read et al. [25] showed that nonrephasing spectra provide a clearer resolution of interexciton energy-transfer pathways than rephasing spectra. By applying specific laser-pulse polarization combinations, their work determined projection angles between excitonic states, revealing distinct energy-transfer processes and offering detailed insights into the interplay between excitonic states.

The development of spatially resolved fluorescence-detected two-dimensional electronic spectroscopy (SF-2DES) has enabled unprecedented spatial and temporal resolution in the study of photosynthetic systems. Tiwari et al. [46] demonstrated that this technique, which integrates femtosecond temporal resolution with submicron spatial resolution, can map the spatial heterogeneity of excitonic structures in photosynthetic bacteria. Their findings revealed that membrane remodeling under varying light-intensity growth conditions induces significant alterations in the excitonic structure of light-harvesting complexes. By analyzing intensity variations of diagonal and cross-peaks in the 2D spectra, they provided critical insights into how environmental factors influence excitonic organization and energy-transfer dynamics.

Overall, with the combined development of high-resolution structural information and ultrafast spectroscopic experiments, research on photosynthesis has advanced further toward analyzing energy flow pathways and coupling relationships between states [51]. 2DES functions as a nonlinear laser spectroscopy method with ultrafast time and frequency resolution, and it provides more accurate descriptions of coherence, coupling, and dynamics in a system than traditional linear spectroscopy. Therefore, it plays a key methodological role in studies of energy transfer in photosynthesis [24, 25, 46-50]. Its application to the FMO complex directly revealed parallel energy pathways and energy flow guided by the spatial distribution of exciton wave functions [24]. Polarization-dependent 2DES improved the resolution of transfer pathways between exciton states by optimizing pulse polarization combinations and by using non-

rephasing spectra, and it quantified projection relations and interactions between different exciton states [25]. Furthermore, SF-2DES combined femtosecond time resolution with submicron spatial resolution, produced images of spatial heterogeneity in exciton structure in photosynthetic bacteria, and showed through analysis of diagonal and cross peaks in the two-dimensional spectra how membrane remodeling under different light intensities reshaped exciton organization in light-harvesting complexes and regulated energy-transfer dynamics [46]. Together, 2DES and its variants provided fine characterization of energy coupling, coherence, and multipath routing in photosynthesis across time, frequency, and space, and they served as essential tools for clarifying the mechanisms of light harvesting and transfer.

2.3 Quantum coherence effects in photosynthetic systems

Quantum coherence effects play a crucial role in photosynthetic systems. Recognizing the significance of quantum coherence, numerous studies have explored leveraging these effects to enhance EET efficiency in photosynthetic systems [43, 52-62].

The mechanism of highly efficient energy capture and transfer in photosynthesis relies on the complex molecular structure of pigment-protein complexes. One of the simplest and most thoroughly investigated cases in the study of photosynthesis is the light-harvesting apparatus of green-sulphur bacteria, as shown in Figure 1. These systems have a very large chlorosome antenna that allows them to thrive in low-light conditions. The energy collected by these chlorosomes is transferred to the reaction center through a specialized structure called the FMO complex. Lee et al. [52] investigated the role of quantum coherence in this transfer process by designing a bichromatic electronic coherent photon echo experiment. They directly probed the electronic coherence between the excitonic states of bacteriochlorophyll (BChl) and bacteriopheophytin in the reaction center of purple bacteria (*Rhodobacter sphaeroides*), revealing how the protein environment preserves quantum coherence and optimizes energy transfer efficiency. Experimental results demonstrated that the coherence between the H and B excitonic states lasts approximately 440 femtoseconds (fs) at low temperatures and 310 fs at higher temperatures. These coherence times significantly exceed predictions from conventional theories.

Theoretical analysis further indicated that electronic coupling alone is insufficient to account for such prolonged coherence times, necessitating consideration of nuclear motion cross-correlations in the protein environment that regulate energy fluctuations of the excitonic states. This strong correlation extends electronic coherence and enhances energy

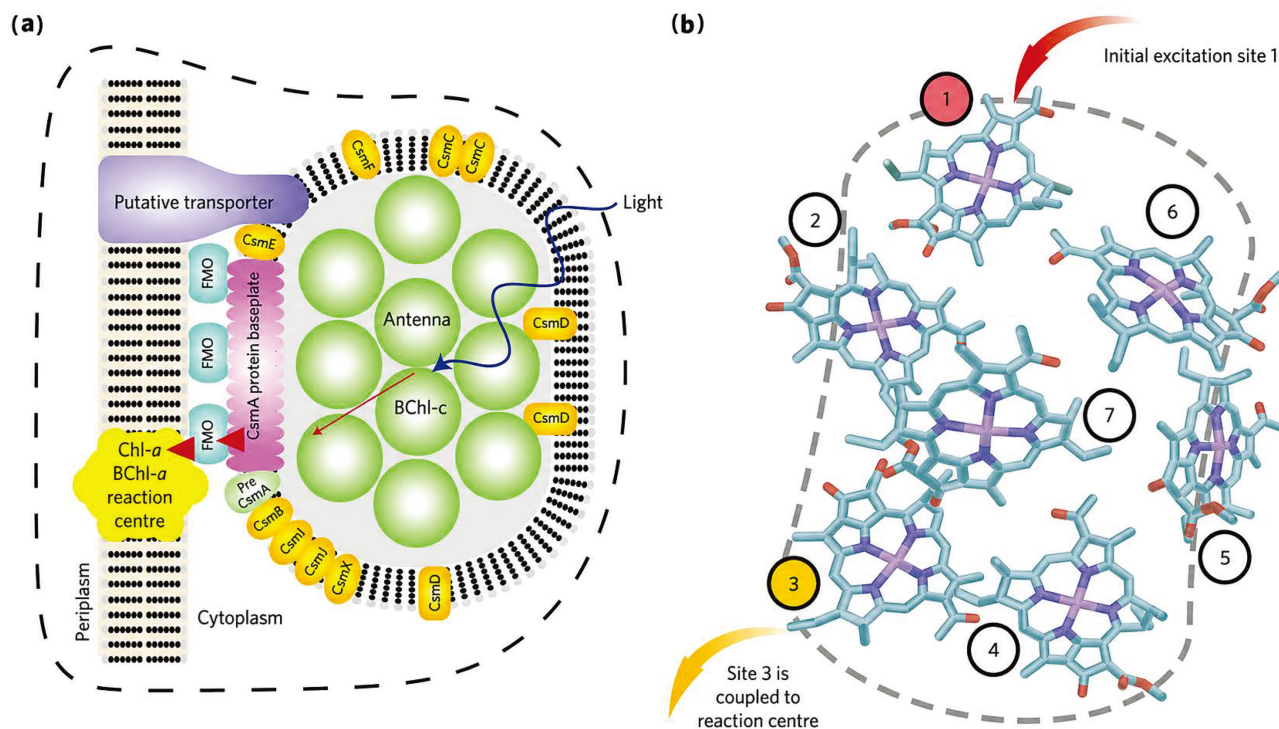


Figure 1 (Color online) A quantum machine for efficient light-energy harvesting. The FMO complex, a well-known part of the light-harvesting system in green sulfur bacteria, shows signs of quantum coherent energy transfer. Both experimental and theoretical studies have examined the mechanism of energy transport in this complex and the extent to which quantum coherence contributes to its light-harvesting function. (a) Schematic of the photosynthetic system in green sulfur bacteria, including the antenna, the energy-transmitting baseplate, the FMO complexes, and the reaction center. The chlorosome antenna contains about 200000 BChl-c molecules and is optimized to capture photons under low-light conditions. (b) X-ray diffraction reveals the BChl-a arrangement in an FMO pigment-protein complex. The FMO complex contains eight BChl-a molecules (seven shown) embedded in a protein scaffold (not depicted). The excitation typically arrives from the chlorosome at site 1, then migrates from one BChl to the next, and upon reaching site 3 it can irreversibly transfer to the reaction center to initiate charge separation. Figure adapted with permission of ref. [2]

transfer efficiency. The study suggests that quantum coherence enables excitons to move rapidly and reversibly through space, efficiently locating energy traps, while the protective role of the protein environment significantly amplifies this process. This study showed that photosynthetic energy transfer does not follow purely incoherent Förster hopping under the independent bath assumption. Instead, it includes significant coherent contributions and coupling to specific vibrational modes, making it necessary to explicitly consider long-range correlations between the system and the bath and the dynamics of coherence in the theoretical framework. This explained the efficient, fast, and reversible search and capture of energy, and it provided clear principles of coherence engineering and control of environmental correlations for the design of bioinspired solar energy conversion materials and devices.

Meanwhile, Engel et al. [53] investigated the energy transfer process in the FMO photosynthetic complex of green sulfur bacteria using 2DES, uncovering the critical role of quantum coherence in efficient energy transfer during photosynthesis. For the first time, they directly observed electronic quantum coherence lasting up to 660 fs at 77 K. This phe-

nomenon was manifested as quantum beat signals between excitons and exceeded the predictions of conventional theories regarding coherence dissipation times. By recording the oscillatory behavior of the lowest-energy excitonic states and their cross peaks in the FMO complex, they found that these oscillations corresponded to quantum coherence between excitonic states. Their study demonstrated that quantum coherence enables the excited state to efficiently sample multiple excitonic states in a wave-like manner, thereby rapidly identifying the optimal energy transfer pathway. This mechanism significantly enhances the efficiency of energy transfer and stands in stark contrast to the traditional hopping model [63].

Panitchayangkoon et al. [59] provided direct evidence that excitonic coherence can couple to excited-state population dynamics during photosynthetic energy transfer. Using 2DES on the FMO complex of green sulfur bacteria, they showed that quantum coherence persisted for extended periods and directly influenced EET through oscillatory excited-state populations. The observed 90° phase relation between population oscillations and coherence supported a quantum-transport origin rather than classical quantum beating or vibrational coupling. Redfield master-equation analysis further

indicated that direct population-coherence coupling drives these oscillations, while dynamic coupling to the protein environment enables reversible energy exchange between the excitonic system and the protein matrix.

This work clarified that the protein environment not only protects coherence but also participates in reversible energy exchange with pigments through strong coupling, revealing at the microscopic level a cooperative flow of energy between excitons and bath modes. This evidence provided direct kinetic support for achieving efficient and robust photosynthetic energy transfer at physical temperatures, and it provided verifiable design guidelines for coherence engineering and environmental control in bio-inspired solar energy materials.

These studies [43, 52-61] indicate that the synergy between quantum coherence and the protein environment is a core mechanism underlying the highly efficient energy transfer in photosynthetic systems. A deeper understanding of these quantum dynamical mechanisms not only expands our knowledge of natural photosynthesis but also provides critical theoretical support and experimental foundations for the design of efficient artificial light-harvesting systems.

Although quantum biology has made striking progress in studies of exciton transport in photosynthesis, the central claims of the field remain highly controversial. In photosynthetic systems, it is still debated whether the long-lived oscillatory signals observed in 2DES can be explained as electronic quantum coherence with biologically functional significance. However, a growing number of studies suggest that these signals can be explained, at least in part, by vibrational coherence or by mixed electronic-vibrational states, rather than by purely electronic coherence [64-67].

By building a dimer model that includes two coupled pigments and intramolecular vibrations, and by combining a nonadiabatic theoretical treatment with simulations of two-dimensional electronic spectra, Tiwari et al. [64] showed that the traditional view attributing long-lived oscillatory signals mainly to electronic coherence is insufficient. This is because purely electronic coherence cannot account for several key spectral features at the same time, and in particular cannot adequately explain the asymmetry in cross-peak oscillation intensity, the phase relations, or the differences between rephasing and nonrephasing signals. They argued that when the energy gap between two exciton states is close to the frequency of an active vibrational mode of a pigment, the vibrational components that are anticorrelated between the two pigments become resonant with the electronic excitation and give rise to pronounced nonadiabatic vibronic mixing. This mixing can not only promote energy transfer between excited states, but also generate a delocalized vibrational wave packet in the ground state, thereby producing os-

cillatory features in two dimensional electronic spectra that resemble, but are not identical to, those usually attributed to electronic coherence. By comparing their results with experimental observations in FMO and other photosynthetic antenna systems, they concluded that the highly efficient energy transfer in photosynthesis cannot be fully explained by long-lived electronic coherence alone, but instead involves a nonadiabatic coupling process in which vibrational and electronic degrees of freedom jointly participate under near-resonant conditions.

Duan et al. [65] reexamined the question of whether photosynthetic energy transfer in the FMO protein depends on long lived electronic coherence by combining two dimensional electronic spectroscopy experiments at room temperature with theoretical calculations. By analyzing the spectral linewidth, the evolution during the waiting time, the decay-associated spectra, and the oscillatory features in the residual signals, the authors showed that electronic coherence in the FMO complex decays rapidly within about 60 fs, which is much shorter than the picosecond lifetime proposed in earlier studies. Therefore, the longer-lasting oscillations observed in the experiments cannot be taken as evidence for the presence of long-lived electronic coherence. They showed that these more persistent oscillations mainly arise from vibrational coherence of chlorophyll molecules rather than electronic coherence between different exciton states.

Maiuri et al. [66] carried out a systematic analysis of the origin of the long-lasting oscillatory signals observed in ultrafast spectroscopy of photosynthetic systems by studying a model of the FMO complex in green sulfur bacteria. They used site-directed mutagenesis to selectively alter the protein environment near individual bacteriochlorophyll molecules, thereby perturbing the exciton energy level structure of the FMO complex, and combined broadband excitation and selective excitation pump-probe experiments to compare the coherent oscillatory features in wild-type and mutant samples at low temperature and at room temperature. They showed that although the mutations significantly changed the absorption spectra and the exciton distribution, the two main oscillation frequencies observed in the experiments and their dephasing time of about 2 ps were almost unaffected. Therefore, these long-lasting oscillatory signals cannot be attributed to electronic coherence between excited states. Furthermore, through selective experiments that excited only the lowest exciton state, the authors showed that the relevant wave packet mainly arose from vibrational coherence in the ground state rather than from long-lived electronic coherence.

Although the role of electronic coherence in photosynthetic energy transfer remains under debate, quantum simulation remains a useful approach for modeling photosynthetic

energy-transfer dynamics.

2.4 Applications of quantum simulation in photosynthesis

In recent years, quantum simulation of photosynthetic systems has made notable advances on various artificial platforms, with the main aim of using controllable quantum systems to replicate the high efficiency and directionality of EET observed in natural light-harvesting complexes. Applications of quantum simulation in photosynthesis include nuclear magnetic resonance (NMR)-based quantum simulations [21, 29–32], superconducting quantum circuit-based quantum simulations [22], and ion trap-based quantum simulations [33–36]. In theory, some quantum algorithms have also achieved the simulation of the Lindblad master equation in open quantum systems, and thus enabled quantum simulation of the dissipative FMO complex and radical pair models related to avian magnetoreception [68, 69].

In quantum simulation of photosynthetic energy transfer, different platforms are suited to different questions. NMR systems are useful for simulating ensemble-averaged coherent dynamics, and controllable dephasing noise can be introduced to study the influence of environmental dephasing on EET. Their advantages are mature control methods and direct comparison with theoretical results such as HEOM. Their main limitations are system scalability and signal readout. Superconducting circuits have strong tunability. Site energies, couplings, and engineered dissipation can be adjusted, which makes this platform useful for studying bright state and dark state dynamics in EET and the effect of controlled noise on energy transfer. Its main limitations come from coherence time and device noise, which can affect deeper or larger simulations. Trapped ions provide precise control of electronic and vibrational degrees of freedom, and are therefore well suited for studying vibrationally assisted energy transfer. This platform can clearly simulate the coupling among donor, acceptor, and vibrational mode, but extension to large pigment networks remains difficult. Overall, these platforms should not be viewed as direct replacements for one another. Rather, they are useful for simulating different levels of physical processes in photosynthetic dynamics.

The Hamiltonian of the photosynthetic system can be expressed as:

$$H = H_S + H_B + H_{SB}, \quad (1)$$

where H_S represents the system Hamiltonian, H_B represents the environment Hamiltonian, and H_{SB} represents the interaction between the system and the environment.

When simulating the quantum dynamics of the photosynthetic system on an NMR platform, the Hamiltonian of the

NMR system can be expressed as:

$$H = H_S + H_{\text{PND}}, \quad (2)$$

where the noise Hamiltonian H_{PND} is given by

$$H_{\text{PND}} = \sum_m \beta_m(t) |m\rangle \langle m|, \quad (3)$$

and $\beta_m(t)$ represents the time-domain distribution of the random noise. The explicit expression for $\beta_m(t)$ is

$$\beta_m(t) = \sum_{j=1}^{N_c} \alpha_z^{(m)} F(\omega_j) \omega_j \cos(\omega_j t + \phi_j^{(m)}), \quad (4)$$

where $\alpha_z^{(m)}$ is the noise amplitude acting on state $|m\rangle$. The discrete frequencies are defined as $\omega_j = j\omega_0$, where ω_0 is the base frequency and $N_c\omega_0$ is the cut-off frequency. $F(\omega_j)$ denotes the modulation function, and $\phi_j^{(m)}$ is a random phase. By performing the Fourier transform of the second-order correlation function of $\beta_m(t)$, the power spectral density $S_m(\omega)$ of the noise can be obtained as:

$$S_m(\omega) = \int_{-\infty}^{\infty} d\tau e^{-i\omega\tau} \langle \beta_m(t+\tau) \beta_m(t) \rangle, \quad (5)$$

which yields

$$S_m(\omega) = \frac{\pi (\alpha_z^{(m)})^2}{2} \sum_{j=1}^{N_c} [\omega_j F(\omega_j)]^2 [\delta(\omega - \omega_j) + \delta(\omega + \omega_j)]. \quad (6)$$

Assuming the noise power spectral density $S_m(\omega)$ has the same form as the spectral density function of the photosynthetic system, the corresponding modulation function $F(\omega_j)$ can be determined. Subsequently, the time-domain distribution $\beta_m(t)$ can be derived, and the noise Hamiltonian H_{PND} can be constructed.

In 2018, Wang et al. [29] employed NMR quantum simulation to investigate EET in photosynthesis by using a linear tetramer model. The model consisted of four chromophores with site energies of 13000, 12900, 12300, and 12200 cm^{-1} , and coupling strengths of 126, 16, 132, and 5 cm^{-1} , respectively, representing typical parameters in photosynthetic systems. Environmental noise, characterized by a Drude-Lorentz spectral density, was incorporated into the simulation to study its impact on the EET process. Experimental results demonstrated that the quantum simulation closely matched the theoretical predictions obtained using the HEOM in the short-time regime, where coherent oscillations were prominently observed. Over longer timescales, the system gradually thermalized, reaching a steady-state equilibrium, thereby validating the role of environmental dephasing in the EET process. Moreover, the study revealed that increasing the number of ensemble samples significantly

reduced the discrepancy between the quantum simulation and theoretical results. For instance, while smaller sample sizes introduced noticeable differences, increasing the sample size to 500 or more led to an almost perfect agreement between the quantum simulation and HEOM calculations. To minimize experimental errors and enhance simulation accuracy, the authors employed the GRAPE algorithm to optimize the pulse sequences. This ensured reliable results and demonstrated the potential of NMR quantum simulation to efficiently reproduce quantum coherence and environmental dephasing effects in photosynthetic energy transfer. The study provides a robust framework for exploring complex EET mechanisms and understanding the role of quantum coherence in natural photosynthetic systems.

In recent years, superconducting quantum circuits, which are highly controllable artificial quantum systems, have been used to simulate the main processes of EET in biological photosynthesis. In 2018, Potočník et al. [22] built a simple three-site model using three tunable transmon qubits and a microwave resonator. Qubits Q1 and Q2 were strongly coupled to produce bright and dark states. Qubit Q3, coupled via the Purcell effect, served as a reaction center to extract excitations. By adding controlled broadband white noise and narrowband Lorentzian noise to Q2, they showed that noise can open an energy path between the bright state and Q3 even when they are not resonant, enabling efficient noise-assisted energy transfer. When the noise spectrum was shaped to match the energy gap, the transfer efficiency increased to 58% compared with 39% under uniform noise. Their measurements also revealed the fluorescence spectra of the bright and dark states, the splitting of the intermediate doublet, and the transition between strong and weak coupling regimes. In both coherent and incoherent excitation experiments, they observed dark-state protection and quantum interference effects. These results clearly demonstrate how quantum coherence and classical decoherence work together to guide energy transport.

Trapped-ion quantum systems are widely used to study quantum dynamics because they allow precise control and measurement of both electronic and motional degrees of freedom [33–36]. In 2018, Gorman et al. [33] employed two $^{40}\text{Ca}^+$ ions to simulate vibrationally assisted energy transfer as it occurs in photosynthesis. The electronic states of the ions are mapped onto donor and acceptor levels. A coupling of strength J between these levels is implemented via a Mølmer-Sørensen interaction on the axial motion mode. The radial rocking mode, prepared in a thermal state, serves as the vibrational environment and is coupled to the donor with strength κ through a local two-tone laser beam. An energy detuning Δ between donor and acceptor is introduced by applying an optical Stark shift via unequal beam powers. In the

experiment, all motional modes are first cooled by sideband cooling to set their mean phonon occupation. The system is then initialized in the state $|DS\rangle$, evolved under the simulated Hamiltonian for a variable time τ , and finally the transfer probability is read out by fluorescence detection. They found that when Δ exceeded J , direct transfer was suppressed, but the vibrational environment bridged the energy gap and produced clear single-phonon resonance peaks in the transfer spectrum. At low temperature, the asymmetry of these peaks revealed the quantum nature of the environment. This study used a minimal and controllable trapped-ion model to demonstrate the key dynamical and spectroscopic features of vibrationally assisted energy transfer. It showed that when a vibrational mode matched the donor-acceptor energy gap in a quantum sense, the environment significantly promoted inter-site energy transfer through single-phonon and multiphonon processes. It also provided controlled evidence for the participation of specific vibrational modes and clarified that the environment does not merely cause dephasing but can also be engineered to enhance transfer.

2.5 Quantum coherence devices

Insights from photosynthesis have inspired a range of design principles for quantum coherent devices aimed at improving light harvesting, charge separation, and energy-conversion performance [39, 70–77]. Rather than merely serving as a subject of quantum simulation, natural photosynthetic systems provide functional blueprints for device engineering.

In plants and algae, the initial conversion of absorbed photons into separated charges is extremely efficient [70, 71]. Blankenship et al. [71] emphasized that natural photosynthesis achieves nearly unity quantum efficiency in its primary energy-storage step. This performance arises from the highly organized arrangement of pigment complexes in the reaction center, where photon absorption is followed by a sequence of selective energy-relaxation and electron-transfer processes that promote efficient charge separation. From the perspective of device design, this picture suggests that artificial light-harvesting systems should not simply maximize absorption, but should instead integrate energy-level alignment, directional transfer pathways, and loss-suppression mechanisms into a coordinated architecture.

Following this bioinspired strategy, Creatore et al. [39] proposed a minimal quantum coherent photocell model in which two dipole-coupled pigments form delocalized bright and dark states that functionally mimic the natural reaction center. In this scheme, optical excitation predominantly populates the bright state, which then relaxes nonradiatively into the dark state. The dark state subsequently transfers an electron to an artificial acceptor. This work illustrates a central

idea in quantum coherent device design, namely that engineering excitonic delocalization and interference can redirect energy flow away from loss channels and toward useful charge-generation pathways.

Subsequent studies further clarified how coherence-related mechanisms in natural photosynthesis can be reformulated as practical design principles for artificial devices. In the PSII reaction center, Romero et al. [74] showed that specific vibrational modes resonate with the energy gaps between exciton and charge-transfer (CT) states, helping to sustain electronic coherence during the ultrafast initial stage of charge separation. For quantum coherent device engineering, this result points to an important strategy: exciton and CT manifolds should be arranged such that their energy splittings are matched to selected vibrational modes or structured environmental fluctuations. Such vibronic resonance can promote directional charge separation, improve pathway selectivity, and help maintain coherence over the time window most relevant for energy conversion.

This line of thinking has also influenced artificial photovoltaic design. Alharbi and Kais [75] analyzed photovoltaic efficiency limits using detailed-balance arguments and proposed that coherence-induced suppression of radiative recombination, analogous to that in photosynthetic reaction centers, could be exploited to enhance solar-cell performance. In such designs, coherent interference between excitonic and CT pathways can reduce loss channels that would otherwise limit conversion efficiency. Brédas et al. [76] further argued that several coherence-related effects, including supertransfer, exchange narrowing, and biased transport in moderately disordered media, can jointly improve exciton diffusion and interfacial charge generation. These studies translate into concrete device guidelines: materials should exhibit small reorganization energies and low Stokes shifts to preserve delocalization and spectral overlap, while donor-acceptor interfaces should remain sufficiently ordered and weakly coupled to support rapid charge separation without enhancing back recombination. In this sense, quantum coherent device design requires the co-optimization of material choice, energy-level structure, intermolecular coupling, and environmental spectral properties.

Beyond molecular-scale energy-conversion devices, photosynthesis-inspired coherence principles have also been extended to larger photonic architectures. Yao and Ai [77] showed that the combination of an energy-level gradient and noise-assisted directionality, both reminiscent of natural light-harvesting systems, can be implemented in coupled-resonator arrays to realize nonreciprocal light transport. In their design, a frequency gradient between neighboring cavities, together with coupling to a thermal environment, leads to strongly asymmetric transmission even in the absence of

magnetic fields or time-dependent modulation. This result highlights that the influence of photosynthetic quantum coherence is not limited to photovoltaics, but can also inspire the design of quantum optical and energy-routing devices that exploit nonequilibrium environments in a constructive way.

These studies show that the relevance of photosynthesis to quantum coherent devices mainly comes from coherent mechanisms in energy transport and charge separation. Bright and dark state dynamics can enhance light absorption while reducing radiative loss. Vibronic coupling among exciton states, CT states, and vibrational modes can support more efficient charge separation pathways. Coherence-assisted pathway selection and energy-level alignment can also help guide energy toward useful output channels. Taken together, these mechanisms provide clear design ideas from natural photosynthesis for artificial light-harvesting and energy-conversion devices.

3 Quantum effects in migratory avian navigation

3.1 Quantum coherence phenomena in migratory avian navigation

Magnetoreception is the ability of certain migratory species to navigate using the Earth's magnetic field [78-82]. Wiltschko et al. [78] proposed a mechanism based on magnetite, suggesting that the magnetite in the bird's beak generates a physical torque in the magnetic field and transmits polarity or intensity information to the brain via the trigeminal nerve.

Qin et al. [83], Guo et al. [84], and Zhou et al. [85] identified the animal magnetosensory receptor gene magnetoreceptor (MagR) and showed that MagR forms rod-like core structures by polymerizing in a magnetic field. In their model, cryptochromes form a light-magnetic coupled complex with intrinsic magnetism that can recognize and respond to external magnetic fields. They further proposed a biocompass structure in which MagR polymerizes into a rod-like core helically wrapped by cryptochrome.

However, the European robin's magnetoreception system functions as an inclination compass, which is insensitive to field polarity, whereas most magnetite-based compass models respond to polarity. Some studies have shown that their navigation relies on photoreceptors [78, 80]. Ritz et al. [82] exposed migratory robins to both the static geomagnetic field and a radio-frequency oscillating field tuned to the radical-pair hyperfine splitting. They found that when the oscillating field was perpendicular to the geomagnetic field, the birds lost their orientation, but when the two fields were parallel,

orientation was restored, demonstrating a resonance effect. In addition, Wiltschko et al. [78, 81] showed that this magnetoreception is highly sensitive to changes in field strength and frequency.

Quantum coherence phenomena in migratory bird navigation involve coherent interconversion between singlet and triplet states mediated by the nuclear spin environment. The directional dependence of geomagnetic signals influences the chemical reaction rates, while quantum phase transitions in the nuclear spin environment enhance navigational sensitivity [28, 86-93].

Magnetoreception denotes the ability of certain migratory taxa to navigate by referring to the Earth's magnetic field [2]. Schulken et al. [94] proposed the RPM to explain the light-dependent nature of magnetoreception. A schematic of the RPM is shown in Figure 2. The standard radical-pair model explains how two bonded molecules, each carrying an unpaired electron, form through a light-activated reaction and enter spin-correlated states as either singlets or triplets. In the presence of the Earth's weak magnetic field and mi-

nor interactions with nearby atomic nuclei, these spin states evolve, switching between singlet and triplet configurations. Because the rate at which each radical pair recombines depends on its spin state, the process yields different chemical products. Organisms can sense these products, and since the relative proportions of singlet and triplet outcomes depend on the alignment of the external magnetic field, the pattern of reaction products conveys directional information, effectively acting as a magnetic compass.

Notably, Kominis [95] was the first to systematically reconstruct the dynamical description of the RPM from the perspective of open quantum systems theory, explicitly arguing that radical-ion-pair reactions should not be regarded merely as conventional spin chemical processes, but rather as open quantum systems jointly governed by environmental coupling, continuous quantum measurement, and nonunitary evolution. He showed that although the phenomenological master equations widely adopted in earlier studies were able to describe the formation of singlet and triplet products within a limited range, these approaches treated spin-

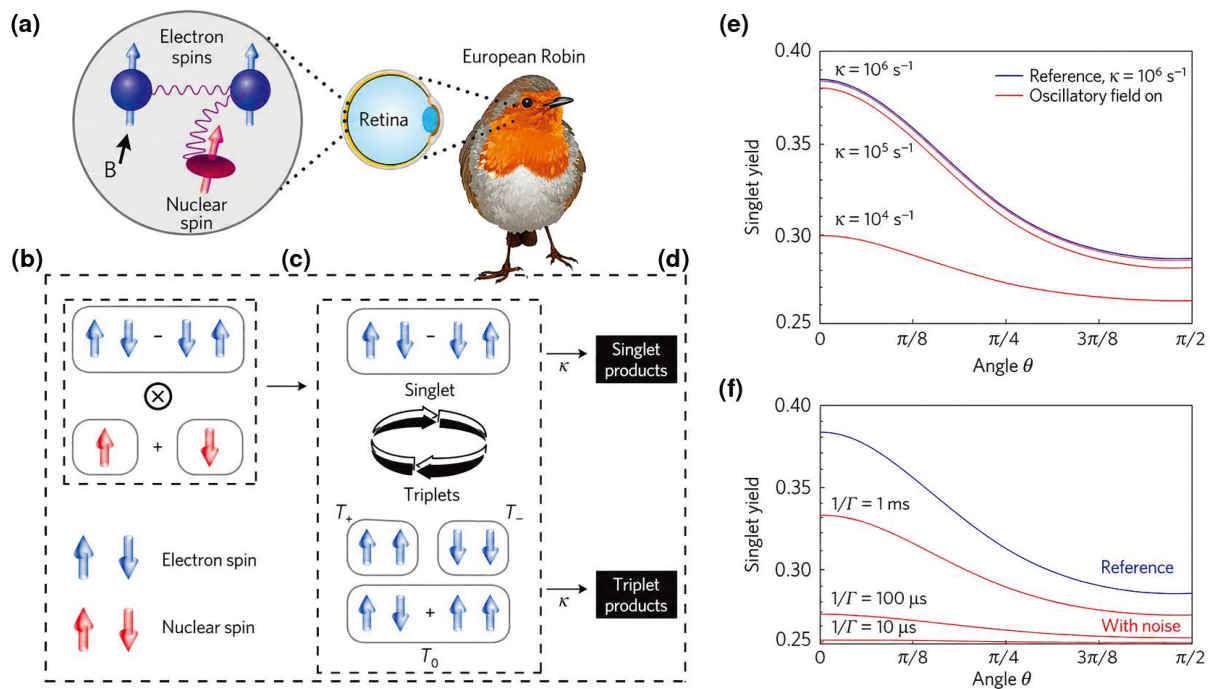


Figure 2 (Color online) The avian quantum compass. The radical pair mechanism for avian magnetoreception accounted for many behavioural observations in several migrating bird species. The main features of the proposed model relied on quantum mechanics, and the model may be viewed as a biological implementation of quantum spin dynamics. (a) A diagram of the radical pair mechanism for magnetoreception that could have been used by European robins and other species. It was proposed to occur within cryptochromes in the retina and proceeded in three steps. First, light drove electron transfer from a donor to an acceptor to create a radical pair. (b) and (c) Second, the singlet and triplet electron spin states interconverted due to external Zeeman and internal hyperfine magnetic couplings. (d) Third, singlet and triplet radical pairs recombined into singlet and triplet products, which were biologically detectable. (e) The singlet yield as a function of the external field angle θ in the presence of an oscillatory field. The blue top curve showed the yield for a static geomagnetic field with $B_0 = 47$ μ T, and the red curves showed the singlet yield when a 150 nT field oscillating at 1.316 MHz was applied perpendicular to the static field. The sensitivity of the compass was the difference in the yield between $\theta = 0$ and $\theta = \pi/2$. A clear change in this sensitivity appeared once κ , the radical decay rate, reached about 10^4 s⁻¹. (f) The singlet yield as a function of the magnetic field angle θ for different noise strengths. The blue curve showed the optimal case without noise with $\kappa = 10^4$ s⁻¹. The red curves showed that a general noise rate $\Gamma > 0.1\kappa$ reduced the sensitivity. These results together indicated that the electron spin state required a very long coherence time. Figure adapted with permission of refs. [2, 28].

selective recombination essentially as a continuous population loss process. As a result, these approaches obscured the genuine quantum coherence and measurement back action inherent in the system and were therefore unable to account satisfactorily for the increasingly complex magnetic field responses observed experimentally. On the basis of this insight, Kominis further proposed that singlet and triplet recombination in radical pairs should be understood fundamentally as continuous quantum measurements of the electron spin state. In this picture, the recombination channels are not merely dissipative outlets, but instead act through selective coupling to probe whether the system occupies the singlet or triplet manifold, which implies that the evolution of radical-ion pairs should be treated within a unified framework combining open quantum systems theory and quantum measurement theory. This work subsequently stimulated broad interest in investigating the RPM from the perspective of open quantum systems.

In 2020, Kominis [96] introduced the quantum relative entropy approach from the resource theory of quantum information into the RPM and systematically proposed and analyzed a formal quantification scheme for singlet-triplet coherence in radical pair systems. Although previous studies [97, 98] had already recognized the important role of singlet-triplet coherence in biological magnetoreception and had proposed several empirical measures of coherence, those earlier definitions still suffered from deficiencies in formal rigor, normalization, and physical intuitiveness, and therefore could not yet be regarded as a formal quantification tool in the strict sense. On this basis, he defined the quantum relative entropy between the radical pair density matrix and its block diagonal form in the singlet and triplet subspaces as a measure of singlet-triplet coherence, thereby providing the first systematic and formal quantification of singlet-triplet coherence in the radical pair mechanism in the sense of quantum resource theory.

Furthermore, in 2025, Kominis [99] proposed a new scheme for quantifying singlet and triplet coherence in radical pair systems, and on this basis discussed how quantum coherence may leave observable signatures at the biochemical and physiological levels. Unlike earlier studies that relied only on empirical descriptions or on general global coherence, this work focused explicitly on the singlet and triplet subspaces that are most physically meaningful in radical pair reactions, and used Wigner-Yanase information to construct a formal measure of singlet-triplet coherence, thereby providing a new quantitative tool for this type of coherence.

Xie [100] has identified, through structural modeling, a long-range intermolecular electron transfer chain within the MagR and cryptochrome protein complex, and has proposed that animal magnetosensing and biological navigation may

be unified by integrating the radical-pair model with the biocompass via spin-dependent electron transport that couples electron spin states with intermolecular electron transfer.

There is an identifiable neural basis in pigeons for processing magnetic information. Wu and Dickman [101] placed awake, head-fixed pigeons in total darkness inside a three-dimensional coil system. They then varied the magnetic field direction and strength step by step and recorded neuronal firing. Their results show that neurons in the vestibular nuclei respond directly to the geomagnetic vector. This provides experimental evidence for how birds process magnetic cues. Earlier work proposed [102] that pigeon magnetoreception relied on magnetite deposits in the beak. However, a recent detailed study [79] found that these deposits are actually macrophages and do not contribute to magnetoreception. These findings do not undermine the radical-pair model. Pigeon magnetoreception is clearly polarity-sensitive, and the RPM can fully explain that feature.

There has been extensive research on the RPM [28, 86, 101, 103–110]. Gauger et al. [28] used the simplest model to describe two electron spins that started in a singlet state, where one electron had an anisotropic hyperfine coupling with a nuclear spin. The geomagnetic field caused interconversion between the singlet state and the triplet state, and spin-selective recombination produced distinguishable chemical products. They computed the dependence of the singlet yield on the direction of the external magnetic field, as shown in Figure 2(e), and found that a weak radio frequency field that disrupted orientation implied that the reaction rate of the radical pair did not exceed about 10^4 s^{-1} . Therefore, the radical pair coherence time was required to be at least tens to hundreds of microseconds. As shown in Figure 2(f), when the environmental noise rate exceeded about 0.1κ , the angular contrast of the singlet yield dropped markedly, emphasizing that sustained long coherence and entanglement are key to maintaining the sensitivity of the singlet and triplet yields to the geomagnetic direction and thus to realizing navigation.

In recent years, many studies have focused on the sensitivity of radical pair reactions to weak magnetic fields. Woodward et al. [106] studied the pyrene anion and dimethylaniline cation radical pair in solution, measuring changes in the singlet state electron-hole recombination yield under radio frequency magnetic fields from 1 to 80 MHz. They found that different deuterated isotopomers produced distinct spectra and proposed a calculation method based on hyperfine coupling and perturbation theory, which successfully explained the observed magnetic field and isotope effects. Maeda et al. [104] carried out experiments in frozen liquid crystal and with photoselection, using a carotenoid porphyrin fullerene

triad to demonstrate anisotropic changes in radical-pair lifetimes under the geomagnetic field strength of about 50 μT . They showed that weak static magnetic fields can alter radical pair kinetics and respond selectively to field direction, providing strong evidence for the chemical compass model.

Ritz et al. [86] found that cryptochrome can transfer an electron to a nearby molecule. This process forms an entangled radical pair. Hyperfine interactions inside the molecule link the electron spin and nuclear spins. This makes the pair very sensitive to external magnetic fields. When the field's direction or strength changes, the conversion rate between spin states also changes. This change alters the yield of the reaction products. Cai et al. [107] used numerical and analytic methods to study how the hyperfine coupling strength of a single nuclear spin affects magnetic sensitivity. They found that a highly directional but weak coupling works best. For a realistic radical pair lifetime, this coupling yields the highest sensitivity.

In addition, Smith et al. [111] focused on possible radical pairs in cryptochrome consisting of a flavin anion radical and either a tryptophan or tyrosine radical, and examined the relation between magnetic-field directional sensitivity and different coherence measures in realistic large systems with up to twenty-one nuclear spins. They used the master equation for spin-selective radical pair recombination as the theoretical basis. Under the assumptions that inter-radical interactions and spin relaxation were neglected, they performed large-scale numerical calculations over many relative radical orientations and compared the ability of electronic coherence and global coherence to explain compass fidelity. The results showed that when only coherence in the electronic subsystem was considered, the relation between electronic coherence and magnetic sensitivity was not stable in either the singlet-triplet basis or the up-down spin basis, and in many models even showed a strong negative correlation. This means that electronic coherence is neither a sufficient index for evaluating compass performance nor an adequate basis for explaining the quantum resource by itself. In contrast, global coherence obtained by treating the electronic and nuclear spins as a whole showed a robust and strong positive correlation with compass anisotropy. This finding indicates that nuclear coherence and electron-nuclear coupled coherence play a central and unavoidable role in magnetoreception. This work supports the view that global coherence is the true quantum resource of avian magnetoreception in models that are closer to physiological conditions and molecular complexity. It also shows that natural systems do not optimize function simply by extending the lifetime of electronic coherence, but by coordinating radical pair lifetime, hyperfine coupling structure, reaction pathways, and overall spin dynamics to achieve high sensitivity to the geomagnetic field.

3.2 Applications of quantum simulation in migratory avian navigation

Applications of quantum simulation in avian navigation include NMR-based quantum simulations [26, 37], superconducting quantum circuit-based quantum simulations [37], and trapped-ion and cavity-QED platform-based quantum simulations that realize critical-spin environments relevant to radical-pair dynamics [38].

For avian magnetoreception, quantum simulation focuses more on radical pair dynamics, singlet-triplet interconversion, magnetic field-dependent yields, and environmental effects. NMR systems and related spin simulation methods are suitable for realizing effective spin Hamiltonians and for studying the dependence of singlet-triplet dynamics and reaction yield on magnetic field direction. Their limitations are scalability and single-shot measurement. Superconducting circuits and digital quantum circuits have strong programmability and are suitable for simulating Lindblad-type open-system dynamics and spin-selective recombination. They can map radical pair dynamics to quantum circuits and obtain singlet and triplet yields through measurement. However, hardware noise and circuit depth can still affect the simulation accuracy. Cavity QED platforms can provide a tunable collective spin environment and are therefore useful for studying critical spin environments, noise effects, and dynamical phase transitions. However, such platforms are usually more suitable for studying model collective spin dynamics than for directly reproducing a full biological radical pair reaction. This comparison helps readers understand the differences among these platforms in coherence time, system scalability, and environmental noise tuning, and also shows which types of biological quantum dynamics each platform is best suited to simulate.

Cai et al. [26] performed a broad-sense quantum simulation of the RPM for avian magnetoreception. They specified a spin Hamiltonian including external magnetic fields and isotropic hyperfine interactions, combined it with an exponential re-encounter probability in a reaction-recombination model, and evolved the full electron-nuclear spin dynamics using a Chebyshev expansion. This framework allowed them to compute the singlet yield Φ_s , the magnetic-field sensitivity Λ , and the angular dependence $\Phi_s(\theta)$. Building on this framework, they incorporated quantum-control pulses into the Hamiltonian to assess their impact. They found that periodic π pulses along the field suppressed S - T mixing and markedly reduced sensitivity. When the field direction was periodically flipped, which degraded the compass function, synchronized X -axis π pulses restored performance. They also showed that an initial $\pi/2$ pulse could distinguish an entangled singlet from a classically correlated mixed state. A

comparison between Py-DMA and $\text{FADH}^{\bullet-}-\text{O}_2^{\bullet-}$ further indicated that, in the former, entanglement correlated with sensitivity and served as a dynamical fingerprint, whereas in the latter, entanglement was short-lived and not essential. Moreover, they predicted that suitable control pulses could induce angular dependence even without a static field, suggesting feasible routes for *in vitro* spin chemistry or behavioral tests of the mechanism and informing the design of bioinspired weak-magnetic sensing.

Keens et al. [112] have shown that in a three-spin system, electron dipole coupling alone produced strong weak-field effects even without nuclear hyperfine interaction. The mechanism was that dipole coupling, together with an external magnetic field, broke the conservation laws and symmetries present in two-spin RPM systems. The field further lifted Kramers degeneracy and caused level crossings or anticrossings, which led to strong directional anisotropy and sharp peaks in the reaction yield. These features are tunable by geometry and exchange coupling. This shifted the understanding of the origin of magnetosensitivity from nuclear hyperfine effects to multi-spin electron interactions and therefore provided a basis for a biomimetic compass that does not rely on a nuclear bath.

Alvarez et al. [113] proposed to map the coherent spin evolution of radical pairs onto a digital quantum computing platform. They studied a prototypical model with two electron spins and one hyperfine-coupled nuclear spin. They used Trotter decomposition to write the Hamiltonian evolution as a sequence of quantum gates that can be implemented in gate-based quantum circuits. Under the condition of symmetric recombination rates, they incorporated the nonunitary reaction loss into the signal calculation through exponential decay in postprocessing. This work showed that, in the noiseless case, a small number of Trotter steps could already reproduce the singlet yield and its angular dependence, which are the most relevant quantities in experiments, and could also remain consistent with the master equation method. They further examined the effect of realistic quantum hardware noise models on the results. They found that noise reduces the signal amplitude and weakens the anisotropy, but the overall shape of the angular response can still be preserved after proper rescaling. This work provides a simple and direct starting point for the digital quantum simulation of the RPM.

On the experimental side, Muniz et al. [38] realized LMG dynamics and a tunable dynamical phase transition with nearly one million strontium atoms in an optical cavity. This platform offers a mature hardware system that can act as an LMG-type environment and, in turn, supports a testable quantum simulation scheme for bio-inspired weak magnetic sensing.

In parallel with these model-driven and hardware-ready advances, Zhang et al. [37] directly studied the open-system dynamics of the RPM using a general quantum algorithm. They mapped the Lindblad master equation into a quantum circuit by applying the Sz.-Nagy unitary dilation, which embeds nonunitary evolution into unitary operations implementable on a circuit. To represent spin-selective relaxation from the electronic singlet and triplet states into product states, they introduced eight projection operators and two shelving states, so that the final singlet and triplet yields could be obtained from the occupations of the shelving states. The system Hamiltonian included two electron spins, one nuclear spin, an anisotropic hyperfine tensor, and an external magnetic field with tunable direction and strength, with the initial state chosen as an electronic singlet and a maximally mixed nuclear spin. The algorithm applied the nonunitary part as a sequence of Kraus operators at each time step, while the unitary part was implemented by diagonalizing the Hamiltonian and applying the corresponding unitary. Each Kraus operator was realized through its unitary dilation, and projection measurements on the computational subspace at each time step yielded the diagonal elements of the density matrix. These quantities were accumulated to obtain the steady-state singlet and triplet yields and their angular dependence. Simulations on the IBM QASM simulator with geomagnetic-scale fields and typical hyperfine strengths showed excellent agreement with classical calculations in both angular dependence and time evolution. Overall, this work reproduced the singlet and triplet yield dynamics and the angular dependence of the avian compass model under the Lindblad framework, providing a verifiable technical route for applying quantum computing to biomagnetoreception.

Quantum simulation provides a testable and scalable way to study the avian navigation mechanism. It can reproduce spin interactions and environmental effects that are difficult to isolate in experiments. It also allows key quantities such as magnetic-field direction dependence and sensitivity to be assessed. With programmable circuits and tunable physical platforms, it maps open system dynamics to observables and thus enables validation of the core processes of the chemical compass. It also lays the groundwork for designing quantum coherent devices for weak-field sensing.

3.3 Quantum devices

Avian magnetoreception has inspired a series of design strategies for quantum coherent devices, especially for weak-field sensing, directional detection, and noise-assisted metrology [26-28, 39, 40, 89, 114-116]. Rather than merely reproducing the spin dynamics of the RPM, these studies

have progressively translated biologically motivated principles into implementable concepts for artificial quantum sensors. In this context, controllable singlet-triplet interconversion, engineered anisotropy, selective environmental coupling, and coherence-assisted signal amplification have emerged as central ideas for device design.

In 2010, Cai et al. [26] introduced quantum control into the radical pair reaction and showed that properly designed control pulses can suppress, recover, or reshape the response of a chemical compass by regulating singlet-triplet dynamics. Their results indicate that quantum control is not only a diagnostic tool for probing the RPM, but also a practical route for device-level functionality. Pulse sequences can be used to switch magnetic sensitivity on or off, enhance angular selectivity, and reduce background responses under oscillating or even vanishing static magnetic fields. From the perspective of quantum coherent devices, this work establishes programmable spin control and initial-state engineering as effective handles for tuning sensitivity, selectivity, and robustness in weak-field sensing architectures.

Building on this foundation, Cai [27] proposed a controllable strong magnetic field gradient to enhance the directional sensitivity of a chemical compass by creating a large local field at one radical while keeping the other near zero. In this design, one radical experiences a large effective local field while the other remains close to the ambient field, thereby generating a strong and controllable directional contrast without requiring complicated intrinsic hyperfine anisotropy. For device engineering, this is a particularly attractive idea because it turns anisotropy from a fixed molecular property into a tunable structural resource. It therefore suggests a practical route toward hybrid quantum sensors in which local magnetic nanostructures, oriented molecular frameworks, or engineered spin environments are integrated to boost field sensitivity.

Recent work has further shown that optimal control methods can be used to tailor spin-selective reaction outcomes in realistic low-field regimes. Chowdhury et al. [115] developed a globally optimal control framework for radical pair reaction yields. They extended the traditional GRAPE method to the control of spin-selective recombination reactions under low magnetic field conditions. In this way, they provide a scalable optimization framework for shaping target response functions in complex open spin systems. This makes it possible to move from qualitative mechanism-inspired models toward quantitatively engineered sensor protocols, in which control waveforms are designed to maximize sensitivity, contrast, or selectivity under realistic decoherence and recombination conditions.

Another major lesson from avian navigation is that environmental noise need not be purely detrimental. When ap-

propriately structured, it can become a functional resource. Xiao et al. [40] proposed that local magnetic field fluctuations (magnetic noise) generated by magnetic proteins drive singlet-triplet interconversion of a radical pair and enhance directional sensitivity to the geomagnetic field, provided that resonance and triplet nondegeneracy conditions were met. A structured noisy environment can be engineered to activate otherwise weak spin-conversion channels and to improve directional discrimination. In this sense, the surrounding spin bath or magnetic environment becomes part of the device architecture rather than an uncontrollable source of degradation. Subsequent high-accuracy treatments of related spin-bath dynamics further support the view that sensitivity can remain high under decohering conditions when the environmental spectrum is properly matched to the relevant transition frequencies [117].

In addition, at the conceptual level, in 2025, Kominis and Gkoudinakis [116] systematically introduced the energy resolution limit from quantum sensing into the study of animal magnetoreception and, on this basis, established an analytical framework that allows a unified comparison of the quantumness of different magnetoreception mechanisms. Taking the RPM, the magnetite mechanism, and the MagR mechanism as examples, they combined three core parameters, namely magnetic sensitivity, sensing volume, and measurement time, to quantitatively evaluate how close these mechanisms are to the quantum limit. This work not only provides a new criterion for understanding the quantumness of animal magnetoreception but also offers an instructive theoretical basis for the design of biomimetic magnetic sensors. Although formulated in the biological context, this framework is also valuable for device research because it connects magnetic sensitivity, sensing volume, and interrogation time within a unified performance metric. As a result, it offers a useful benchmark for evaluating how closely biomimetic magnetic sensors approach fundamental quantum limits.

The link between avian magnetoreception and quantum coherent devices mainly comes from the spin-dependent response in radical pair dynamics. By tuning singlet-triplet dynamics, one can change the response of the system to weak magnetic fields. Molecular orientation, hyperfine structure, and local magnetic field gradients can enhance the anisotropic response and make the system more sensitive to the field direction. The magnetic-noise mechanism discussed above is mainly associated with avian magnetoreception. Under resonance and triplet non-degeneracy conditions, local magnetic field fluctuations can promote singlet-triplet interconversion and enhance directional sensitivity. For practical device design, these mechanisms still need to be assessed through quantities such as sensitivity, response time, and sensing volume.

Overall, research inspired by avian navigation is gradually establishing a design framework for quantum coherent sensing devices. Instead of treating the RPM solely as a biological phenomenon to be simulated, recent work has extracted from it a set of implementable strategies, including programmable spin control, engineered anisotropy, noise-assisted coherence management, and performance benchmarking near quantum limits. These advances provide a realistic path from biological inspiration to the realization of highly sensitive, directional, and controllable quantum coherent sensors.

4 Conclusion

Overall, quantum effects have broad applications in biological systems. In photosynthesis, energy transfer can occur with remarkably high efficiency. Migratory birds have a light-dependent magnetic compass that can detect the direction of the Earth's magnetic field with high precision. Effective simulation of quantum effects in biological systems and their translation into quantum coherent devices may enable advances in efficient energy use and high-precision quantum sensing.

In this review, we first introduce several theories used to study photosynthesis, such as Förster theory and Modified Redfield theory [4-7]. Within their respective regimes of validity, these methods provide useful descriptions of energy transfer between molecules. We then describe the development of 2DES. 2DES has played a key role in research on photosynthesis. It can reveal the coupling structure, energy transfer pathways, and quantum coherence in pigment-protein complexes, and thus provides experimental tools for studying quantum effects in photosynthesis. Using 2DES, researchers have shown how the protein environment preserves quantum coherence and optimizes energy transfer efficiency. They have observed electronic quantum coherence and revealed its key role in efficient energy transfer during photosynthesis. These theoretical and experimental advances lay the groundwork for artificial high-efficiency solar-energy conversion and the development of quantum coherent devices.

At the same time, quantum simulation has provided a controllable and computationally efficient route for studying photosynthetic dynamics on platforms such as NMR systems, superconducting circuits, and trapped ions. Across these platforms, quantum simulations of photosynthetic systems have reproduced coherent oscillations consistent with benchmark calculations such as HEOM, while reducing the cost of directly treating complex open-system dynamics. Inspired by these findings, researchers have begun to use quan-

tum coherence to build devices that achieve efficient energy transfer. Creatore et al. [39] showed that a design that uses exciton coherence can increase photocurrent and maximum power output compared with uncoupled pigments. Alharbi and Kais [75] used a coherence-based recombination suppression mechanism from the photosynthetic reaction center. Their simulations indicate that “quantum coherent” solar cells could exceed the Shockley-Queisser limit by several tens of percent. Brédas et al. [76] suggested using low Stokes shift dyes, such as phthalocyanines and squaraines, in organic photovoltaics. In addition, Yao and Ai [77] applied the concept of a photosynthetic energy level gradient together with noise-assisted directionality to coupled resonator arrays, achieving highly unidirectional energy transfer in an isothermal and noisy environment. A growing body of theory and experiment shows that introducing quantum coherence into artificial systems can greatly enhance energy transfer efficiency, opening a path to quantum engineering methods for solar energy conversion and light harvesting technologies.

We next introduce quantum coherence in animal navigation that uses the geomagnetic field. Researchers usually explain animal navigation with mechanisms based on magnetite, MagR genes, and cryptochromes. Schulten et al. [94] proposed the RPM to explain the light-dependent nature of magnetoreception. Radical pairs created by photoexcitation are initially in a quantum superposition of singlet and triplet states, and the spins of the two unpaired electrons are quantum coherently coupled. The geomagnetic field modulates singlet-to-triplet coherent oscillations and interconversion rates through the Zeeman interaction and anisotropic hyperfine interactions.

Similarly, quantum simulation provides a useful approach for studying radical-pair dynamics relevant to animal magnetoreception. NMR and superconducting platforms have been used to simulate spin dynamics and reaction yields in radical-pair models, while cavity-QED platforms provide tunable collective spin environments for studying related noise and critical-dynamics effects. Inspired by animal navigation, researchers use the RPM to build high-precision chemical compasses. Cai [27] proposed a controllable strong magnetic field gradient that enhances directional sensitivity by creating a large local field at one site while keeping the other near zero. Xiao et al. [40] showed that, as long as resonance and triplet nondegeneracy hold, local magnetic field fluctuations generated by magnetic proteins, that is, magnetic noise, can drive singlet-to-triplet interconversion in radical pairs and enhance sensitivity to the geomagnetic field, indicating that magnetic noise can increase metrological precision.

These studies have shown the connection among quantum biology, quantum simulation, and quantum coherent devices, but several issues still need further study. For photosynthesis,

future work should more clearly distinguish the roles of electronic coherence, vibrational coherence, and vibronic coupling in EET, and determine whether these coherent effects can provide a real functional advantage under physiological conditions. For avian magnetoreception, it remains important to clarify how radical pair dynamics, spin relaxation, magnetic noise, and biological environments jointly affect directional sensitivity. In quantum simulation, many current studies still focus on small-scale models, and future work needs to move toward larger photosynthetic pigment networks and more realistic radical pair models. For quantum coherent devices, the key question is whether these bioinspired mechanisms can lead to measurable improvements on practical platforms, such as higher efficiency, better robustness, and stronger scalability.

In summary, a growing number of studies have shown that quantum simulation provides an efficient and powerful approach for investigating quantum coherence effects in biological systems. At the same time, quantum coherent devices inspired by photosynthetic energy transfer and avian magnetoreception offer a feasible route toward more efficient energy utilization and high-precision sensing. These advances not only deepen our understanding of quantum biology, but also promote the development of bioinspired quantum technologies. Nevertheless, ongoing debates over the origin, lifetime, and functional role of quantum coherence in biological systems highlight the need for more accurate theoretical models, more direct experimental evidence, and more scalable quantum simulation platforms.

This work was supported by the Quantum Science and Technology-National Science and Technology Major Project (Grant No. 2023ZD0300200), the National Natural Science Foundation of China (Grant Nos. 62461160263 and 62131002), the Beijing Advanced Innovation Center for Future Chip (ICFC), Tsinghua University Initiative Scientific Research Program, and Guangdong Provincial Quantum Science Strategic Initiative (Grant No. GDZX2505004).

Conflict of interest The authors declare that they have no conflict of interest.

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