Magnetic Noise Enabled Biocompass

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The discovery of magnetic protein provides a new understanding of a biocompass at the molecular level. However, the mechanism by which magnetic protein enables a biocompass is still under debate, mainly because of the absence of permanent magnetism in the magnetic protein at room temperature. Here, based on a widely accepted radical pair model of a biocompass, we propose a microscopic mechanism that allows the biocompass to operate without a finite magnetization of the magnetic protein in a biological environment. With the structure of the magnetic protein, we show that the magnetic fluctuation, rather than the permanent magnetism, of the magnetic protein can enable geomagnetic field sensing. An analysis of the quantum dynamics of our microscopic model reveals the necessary conditions for optimal sensitivity. Our work clarifies the mechanism by which magnetic protein enables a biocompass.

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Introduction.—Experiments have shown that migrating birds employ the geomagnetic field for orientation and navigation [1,2]. To understand the physical origin of the navigation of animals, several physical models [3,4] have been proposed. A widely accepted model is the radical pair model, suggested by Ritz *et al.* in Ref. [5]. This model assumes that the navigation process is governed by radical pairs, with each pair consisting of an unpaired electron spin [6]. The pairs are usually created via photon excitation and form a spin singlet state [7–9]. In the geomagnetic field and the magnetic field provided by the local molecular environment, the spin singlet state undergoes a transition to spin triplet states [9,10]. The radical pair is metastable and eventually produces different chemical products according to the spin states of the radical pair [11–13], and the chemical products determine the subsequent navigation behavior [5,11].

In the radical pair model, we focus on the singlet-triplet interconversion mechanism at the molecular level. Homogeneous geomagnetic fields cannot change the spin singlet or triplet state because of the conservation of the total spin angular momentum. Only inhomogeneous magnetic fields can cause transitions between the spin singlet and the spin triplet states. Microscopically, inhomogeneous magnetic fields are provided by the surrounding magnetic moments (either nuclear spins or electron spins) in biological molecules. Through the interaction between these spins, the radical pair can feel an effective magnetic field. Nevertheless, the detailed microscopic origin of the singlet-triplet interconversion process remains unclear.

Previous studies have focused on the nuclear spin environment around the radical pair. For example, experiments found that the $FADH^{\bullet} - O_2^{\bullet -}$ molecule (which couples the radical pair via the hyperfine interaction) is relevant to animal navigation [14–17]. Theoretically, studies in Refs. [13,18–21] showed that the nuclear spin environment is capable of providing local magnetic fields and enabling a biocompass. Our analysis shows that the nuclear spin concentration and the anisotropic dipolar coupling between the radical pair spins and the bath nuclear spins play important roles to enable a biocompass [22]. In addition to progress on the nuclear spin bath, Ref. [28] reported a new putative magnetic receptor (MagR) and showed that the MagR forms a rod-like magnetosensor complex with the radical pair in the photoreceptive cryptochromes. The MagR consists of an Fe-S cluster protein, with the d electrons in the Fe atom contributing the electron spins [29,30]. It is reasonable to assume that the navigation behavior arises from the effect of an electronic spin bath.

However, the microscopic role of the magnetic protein is under debate. In Ref. [31], the author pointed out that electron spins are hardly polarized at room temperature and cannot produce a significant single-triplet transition process. Therefore, it is crucial to elucidate what makes the biocompass possible in the absence of a finite magnetization in the MagR. In this Letter, we propose that the magnetic field fluctuation, rather than the mean magnetization, is capable of producing the spin singlet and triplet transition. The electron spin bath of the MagR introduces a fluctuating local magnetic field to the nearby radical pairs via the magnetic dipole-dipole interaction, and this local magnetic field actually enables singlet-triplet interconversion.

First, with a semiquantitative analysis of a radical pair coupling to an electron spin bath in the geomagnetic field, we find two necessary intuitive requirements for the local magnetic field that need to be satisfied: (i) the strength of the noise magnetic field must be comparable to the

geomagnetic field ($\sim 10^{-1}$ Gauss), and (ii) the local magnetic field should have directional dependence. Then, we establish a microscopic model that describes the spin dynamics of the radical pair in an electron spin bath. With theoretical analysis and numerical calculations, we find that the singlet fidelity of the radical pair can exhibit a sensitive geomagnetic field direction dependence. Our work provides new insights into the understanding of the biocompass mechanism.

Theoretical model.—We consider a radical pair interacting with a spin bath described by the following Hamiltonian:

$$H = H_{\mathrm{rp}} + H_{\mathrm{bath}} + H_{\mathrm{int}}, \tag{1}$$

where H_{rp}, H_{bath}, and H_{int} are the Hamiltonians of the radical pair, the bath spin and their interaction, respectively. The radical pair consists of two electron spins $\mathbf{S}_1$ and $\mathbf{S}_2$, forming the singlet state $|S\rangle = (|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)/\sqrt{2}$ and triplet states $|T_0\rangle = (|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle)/\sqrt{2}$, $|T_+\rangle = |\uparrow\uparrow\rangle$, and $|T_-\rangle = |\downarrow\downarrow\rangle$ [5]. In the singlet-triplet representation, the radical pair Hamiltonian is diagonalized as

$$H_{\mathrm{rp}} = \sum_k \omega_k |\phi_k\rangle\langle\phi_k|, \quad \text{for } |\phi_k\rangle \in \{|S\rangle, |T_0\rangle, |T_+\rangle, |T_-\rangle\}, \tag{2}$$

where ω_k is the energy of the singlet or triplet state $|\phi_k\rangle$. The radical pair is subjected to a magnetic environment consisting of N interacting spins $\{\mathbf{J}_i\}_{i=1}^N$.

$$H_{\mathrm{bath}} = \sum_{i=1}^{N} \gamma_i \mathbf{B}\cdot\mathbf{J}_i + \sum_{i>j=1}^{N} \mathbf{J}_i \cdot \mathbb{D}_{ij} \cdot \mathbf{J}_j, \tag{3}$$

where $\mathbf{B}$ is the geomagnetic field, γ_i is the gyromagnetic ratio of the ith bath spin, and $\mathbb{D}_{ij}$ is the coupling tensor between $\mathbf{J}_i$ and $\mathbf{J}_j$. The radical pair spins couple to the bath spins through the interaction Hamiltonian

$$H_{\mathrm{int}} = \sum_{k,i} \mathbf{S}_k \cdot \mathbb{A}_{ki} \cdot \mathbf{J}_i \equiv \sum_{k=1,2} \gamma_e \mathbf{S}_k \cdot \mathbf{b}_k, \tag{4}$$

where γ_e is the electron spin gyromagnetic ratio, $\mathbb{A}_{ki}$ is the coupling tensor and $\mathbf{b}_k$, as seen by the radical pair spin $\mathbf{S}_k$, is the effective magnetic field caused by the bath spins.

Indeed, Eqs. (1)–(4) are quite general Hamiltonians describing the interacting spins. Since the precise electronic structure of the radical pair and the bath spins of the biocompass system is still unclear, we did not specify the details of the singlet or triplet energies ω_k and the concrete forms of the coupling tensors $\mathbb{A}_{ki}$ and $\mathbb{D}_{ij}$ in Eqs. (1)–(4). However, we assume that the random motion of the spins (typically with a time scale $>$ ms [32]) is not fast enough to average out the spin dynamics of the radical pair (typically $\sim\mu$s [11–13]). Nevertheless, we will show that we still need some reasonable assumptions for ω_k, $\mathbb{A}_{ki}$, and $\mathbb{D}_{ij}$ based on the known structure of the magnetic protein to make the coupled system described by Eqs. (1)–(4) exhibit strong sensitivity to the geomagnetic field direction.

Magnetic fluctuation.—We study the quantum dynamics of the radical pair in an unpolarized spin bath. The radical pair is initially prepared in a singlet state with $\rho_{\mathrm{rp}}(0) = |S\rangle\langle S|$, and the bath spins are in a high-temperature mixed state

$$\rho_{\mathrm{bath}}(0) = \bigotimes_{i=1}^{N} \frac{\mathbb{I}_i}{\mathrm{Tr}[\mathbb{I}_i]}, \tag{5}$$

where $\mathbb{I}_i$ is the identity operator for the ith spin. Starting from the initial state $\rho(0) = \rho_{\mathrm{rp}}(0) \otimes \rho_{\mathrm{bath}}(0)$, the system evolves to $\rho(t)$ driven by the Hamiltonians in Eqs. (1)–(4). We focus on the singlet state fidelity $P_S(t) = \mathrm{Tr}[|S\rangle\langle S|\rho(t)]$ of the radical pair and its dependence on the geomagnetic field direction [5].

The field difference $\delta\mathbf{b} = \mathbf{b}_1 - \mathbf{b}_2$ experienced by the two spins of the radical pair causes the singlet-triplet conversion. Before presenting full quantum mechanical calculations of the singlet fidelity $P_S(t)$, we present a qualitative analysis of the effect of $\delta\mathbf{b}$. One of the key concerns is that the mean value of the field difference $\delta\mathbf{b}$ vanishes at room temperature, i.e., $\mathrm{Tr}[\rho_{\mathrm{bath}}(0)\delta\mathbf{b}] \equiv 0$. This condition strongly challenges the role of the MagR in the biocompass mechanism. However, the fluctuation of $\delta\mathbf{b}$ can also cause the singlet-triplet conversion. Specifically, in the following, we consider the variation in the projection of $\delta\mathbf{b}$ along the direction $\mathbf{n_B}$ of the external magnetic field $\mathbf{B}$, i.e., $\delta b_{\mathbf{n_B}}^2 = \mathrm{Tr}[\rho_{\mathrm{bath}}(0)(\mathbf{n_B}\cdot\delta\mathbf{b})^2]$. Here, $\mathbf{n_B}$ is given by the Euler angle θ, ϕ of $\mathbf{B}$. We will present requirements for the field difference $\delta\mathbf{b}$ to play an important role in the biocompass.

First, the fluctuations $\delta b_{\mathbf{n}_B}$ should have comparable strengths to the geomagnetic field $\mathbf{B}$. In the weak fluctuation limit $|\delta b_{\mathbf{n}_B}| \ll |\mathbf{B}|$, the system evolution will be dominated by the homogeneous geomagnetic field $\mathbf{B}$, and singlet-triplet conversion can hardly occur. However, in the opposite limit $|\delta b_{\mathbf{n}_B}| \gg |\mathbf{B}|$, the geomagnetic field $\mathbf{B}$ will have a negligible influence on the dynamics of $P_S(t)$. In both limiting cases, the system does not exhibit a biocompass function. Using the structure obtained in Refs. [22,28] and assuming electronic dipolar coupling between the radical pair spins and the bath spins in Eq. (4), we find that the magnitude of the coupling tensor $\mathbb{A}_{ki} \sim 10^1$ MHz, corresponding to the strength of the fluctuations $\delta b_{\mathbf{n}_B} \sim 10^{-1}$ Gauss [see Fig. 1(b)], is on the same order as the geomagnetic field.

Second, the fluctuation of $\delta\mathbf{b}$ should be sensitive to the direction of the geomagnetic field. This condition requires the coupling $\mathbb{A}_{ki}$ between the radical pair and spin bath to be anisotropic. Indeed, the dipolar coupling between the electron spins satisfies this requirement. Furthermore, the rodlike structure also enhances the anisotropicity of the field fluctuation, since the axial and azimuthal directions

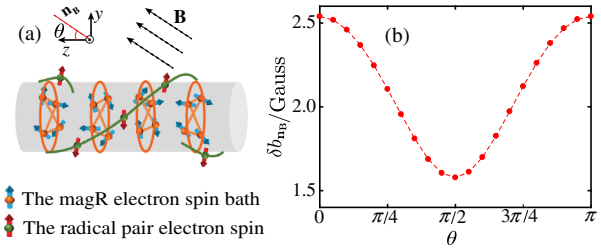

FIG. 1. (a) Illustration of the structure of the bath electron spins and the radical pair. The spins are fixed in the proteins. (b) Magnetic field fluctuation along the geomagnetic field direction $\delta b_{\mathbf{n}_B}$ as a function of the geomagnetic field direction θ.

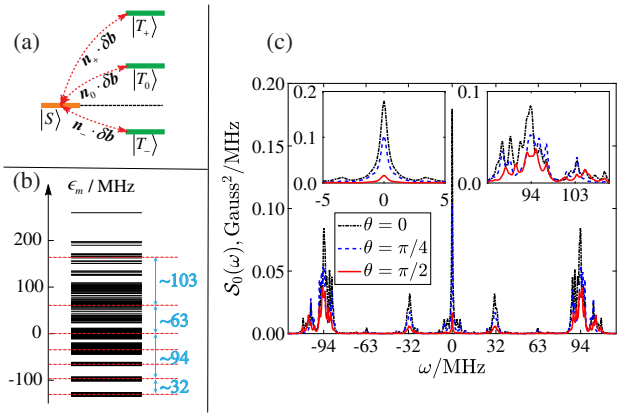

FIG. 2. (a) Illustration of the radical pair's energy spectrum and the corresponding noise component during the transition. (b) The energy spectrum of the two rings in the MagR (see text). (c) The noise spectrum $\mathcal{S}_0(\omega)$ for the two rings in different geomagnetic directions, which shows broadened peaks near 0,32,63,94, and ± 103 MHz. Here, for the convenience of illustration, we add Lorentzian broadening of 0.3 MHz $\ll \Delta\omega_{peak}$.

are obviously inequivalent. As an example, Fig. 1(b) shows that the fluctuation magnitude changes by a factor of ~ 2 as the geomagnetic field direction varies by π.

With these two intuitive requirements, we find that the dipolar coupling between the radical pair and the MagR spins is a promising candidate to explain the microscopic mechanism of the biocompass. In the following, we discuss the optimal conditions of magnetosensation through the quantum dynamics of the system.

Optimization of magnetosensation.—In the system defined by Eqs. (1)–(4), we focus on the dynamics of the singlet fidelity $P_S(t)$ of the radical pair spins. A full analytical calculation is usually not available for a system of interacting electron spins. Here, we first analyze the short-time behavior of $P_S(t)$. With the short-time approximation, we obtain the qualitative requirements for ω_k, $\mathbb{A}_{ki}$, and $\mathbb{D}_{ij}$ to achieve optimal magnetosensation of the singlet fidelity, which are further confirmed by numerical simulations.

The effective field difference $\delta\mathbf{b}$ induces transitions from the singlet state $|S\rangle$ to the triplet states $|T_0\rangle$ and $|T_\pm\rangle$ and causes a loss of the singlet fidelity. Specifically, we choose the quantization axis (the z axis) along the direction of the geomagnetic field. As shown in Fig. 2(a), the longitudinal component $\delta b_z = \delta\mathbf{b}\cdot\mathbf{e}_z$ induces the transition $|S\rangle \to |T_0\rangle$, while the transverse components $\delta b_\pm = \delta\mathbf{b}\cdot\mathbf{n}_\pm$ with $\mathbf{n}_\pm = (\mp\mathbf{e}_x - i\mathbf{e}_y)/\sqrt{2}$ result in the transitions $|S\rangle \to |T_\pm\rangle$. The field difference $\delta\mathbf{b}$ is nonstatic in a full quantum mechanical treatment. The dynamics of the effective field difference is determined by the interaction within the bath spins as

$$\delta\mathbf{b}(t) = e^{iH_{\text{bath}}t}\delta\mathbf{b}(0)e^{-iH_{\text{bath}}t}. \tag{6}$$

The expectation value of the field difference $\langle\delta\mathbf{b}(t)\rangle$ vanishes. However, $\delta\mathbf{b}(t)$ has finite fluctuations: $\langle\delta\mathbf{b}(t)\delta\mathbf{b}(t')\rangle = \mathrm{Tr}[\delta\mathbf{b}(t)\delta\mathbf{b}(t')\rho_{\text{bath}}(0)] \neq 0$.

To understand the dynamic properties of the field difference $\delta\mathbf{b}(t)$, it is necessary to investigate the interaction within the bath spins. As illustrated in Fig. 1(a), the MagR spin bath consists of several ring structures. Within a ring, the distance between the spins is approximately 1–2 nm, while the interring distance is greater than 5 nm (see [22] for the coordinates of the electron spins). Suppose that the spins are all coupled through the magnetic dipole-dipole interaction, i.e., $\mathbb{D}_{ij} = (\mu_0\gamma_e\gamma_e\hbar/r_{ij}^3)\times(1 - 3\hat{\mathbf{r}}_{ij}\hat{\mathbf{r}}_{ij})$, with r_{ij} being the distance between two spins and $\hat{\mathbf{r}}_{ij}$ being the unit coordinate vector. Since the dipolar interaction strength decays as r_{ij}^{-3}, the coupling of the spins within a ring ($\sim 10^1$ MHz) is much stronger than that in different rings ($< 10^0$ MHz). Figure 2(b) shows the energy spectrum ϵ_m of H_{bath} obtained by diagonalizing the Schrödinger equation

$$H_{\text{bath}}|\psi_m\rangle = \epsilon_m|\psi_m\rangle, \tag{7}$$

with $|\psi_m\rangle$ being the eigenstate. The energy spectrum ϵ_m forms several discrete bands around 0, ± 32, ± 63, ± 94, and ± 103 MHz, resulting from the strong interaction of the electron spins within a ring. Each band is further broadened due to the weak interaction of the electron spins between the rings.

With the transition probability $P_{S\to T_\alpha}(t)$ from the singlet state $|S\rangle$ to the triplet states $|T_\alpha\rangle$ (for $\alpha = 0$ or $\pm$), the singlet fidelity is expressed as

$$P_S(t) = 1 - \sum_\alpha P_{S\to T_\alpha}(t). \tag{8}$$

In the short-time limit, the transition probability $P_{S\to T_\alpha}(t)$ is approximated as [22,33,34]

$$P_{S\to T_\alpha}(t) = \gamma_e^2\int_{-\infty}^{\infty}\mathcal{S}_\alpha(\omega)F(t,\omega;\omega_{ST_\alpha})d\omega \tag{9}$$

with $\omega_{ST_\alpha} = \omega_S - \omega_{T_\alpha}$. In Eq. (9), the function $\mathcal{S}_\alpha(\omega)$ is the power spectrum of the effective field difference δb_α

$$\mathcal{S}_\alpha(\omega) = \frac{1}{2^N}\sum_{m,n}|\langle\psi_m|\delta b_\alpha|\psi_n\rangle|^2\delta(\omega-\epsilon_{mn}) \quad (10)$$

with $\epsilon_{mn} = \epsilon_m - \epsilon_n$; the function $F(t,\omega;\omega_{ST_\alpha})$, defined as

$$F(t,\omega;\omega_{ST_\alpha}) = \frac{\sin^2(\frac{\omega t+\omega_{ST_\alpha}t}{2})}{(\omega+\omega_{ST_\alpha})^2}, \quad (11)$$

is regarded as a spectrum filter function in the frequency domain, which exhibits a peak centered at ω_{ST_α} with width $\Delta\omega_{\text{filter}} = 1/t$ [33]. Moreover, to directly relate the singlet fidelity $P_S(t)$ to the biochemical process, we define the singlet productivity on a relevant timescale

$$\Phi_S(\tau;\theta;\phi) = \frac{1}{\tau}\int_0^\tau P_S(t;\theta;\phi)dt, \quad (12)$$

which is a function of the geomagnetic direction. Here, τ is the relevant time scale in the radical pair model, chosen to be 1 μs in the subsequent discussion [11,13].

The power spectrum $\mathcal{S}_\alpha(\omega)$ describes the dynamic property of the field difference δb_α in the frequency domain. As an example, Fig. 2(c) shows the power spectrum $\mathcal{S}_0(\omega)$ [see [22] for more results for $\mathcal{S}_\pm(\omega)$]. Due to the band structure of the eigenenergies ϵ_m [see Fig. 2(b)], the power spectrum exhibits broadened discrete peaks around specific transition frequencies [e.g., $\omega_{\text{peak}} = 0, \pm 32, \pm 63, \pm 94$, and ± 103 MHz for $\mathcal{S}_0(\omega)$ shown in Fig. 2(c)], with a typical peak width $\Delta\omega_{\text{bath}} \sim 10^1$ MHz. Furthermore, due to the anisotropic dipolar coupling between the spins and the rodlike geometric configuration of the MagR, the power spectrum exhibits a dependence on the geomagnetic field direction. Figure 2(c) shows that the amplitudes of the power spectrum peaks of $\mathcal{S}_0(\omega)$ are very sensitive to the different geomagnetic field directions.

The overlap between the power spectrum $\mathcal{S}_\alpha(\omega)$ and the filter function $F(t,\omega;\omega_{ST_\alpha})$ determines the loss of the singlet fidelity, as shown in Eq. (9). With this observation, we propose the following necessary conditions for a robust biocompass to exhibit a strong dependence on the geomagnetic field direction.

First, at least one of the peaks of the power spectrum must be in resonance with the singlet-triplet transition, i.e., $|\omega_{ST_i} - \omega_{\text{peak}}| < \Delta\omega_{\text{bath}}$. Essentially, the singlet fidelity loss in this case can be understood by the Fermi golden rule, where the MagR spins provide resonant perturbations that cause the singlet-triplet transition of the radical pair [33]. Figure 3(a) shows an opposite example, in which the frequencies of the power spectrum peaks and the singlet-triplet transition are mismatched. In this case, the radical pair spins can hardly transition from the singlet state to the triplet states. Thus, the singlet productivity is very close to unity and has a negligible geomagnetic direction dependence [Fig. 3(d)].

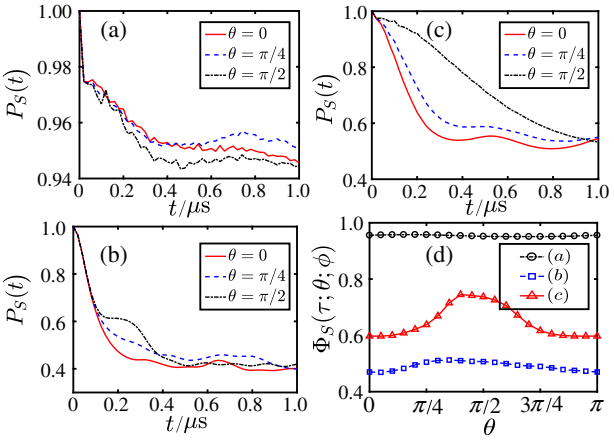

FIG. 3. The numerical result of the singlet fidelity as a function of time for different representative geomagnetic directions: (a) when all ω_{ST_i} do not overlap with the filter spectrum ($\omega_{\text{ST}_0} = 20$ MHz, $\omega_{\text{ST}_+} = 23$ MHz, $\omega_{\text{ST}_-} = 17$ MHz), (b) when all ω_{ST_i} overlap with the filter spectrum but all the triplets are degenerate ($\omega_{\text{ST}_0} = 0.1$ MHz, $\omega_{\text{ST}_\pm} = \pm 3.0$ MHz), and (c) when ω_{ST_0} overlaps with the noise spectrum $\mathcal{S}_0(\omega)$ while the others do not($\omega_{\text{ST}_0} = 0.01$ MHz, $\omega_{\text{ST}_\pm} = \pm 20.0$ MHz). (d) The singlet productivity as a function of the geomagnetic field direction θ for $\phi = 0$ [35].

Second, the energy splittings of the triplet states are crucial to the biocompass. Assuming that the resonance condition mentioned above is satisfied, and the three triplet states are nearly degenerate ($\omega_{T_\alpha} \approx \omega_T$). In this case, Eq. (8) becomes

$$P_S(t) \approx 1 - \gamma_e^2\int_{-\infty}^{\infty}\left(\sum_\alpha \mathcal{S}_\alpha(\omega)\right)F(t,\omega,\omega_{ST})d\omega, \quad (13)$$

where $\omega_{ST} = \omega_S - \omega_T$ and the total power spectrum is

$$\sum_\alpha \mathcal{S}_\alpha(\omega) = \frac{1}{2^N}\sum_{m,n}|\langle\psi_m|\delta\mathbf{b}|\psi_n\rangle|^2\delta(\omega-\epsilon_{mn}). \quad (14)$$

Note that the total power spectrum depends on the magnitude of the field difference, which is insensitive to the geomagnetic field direction. Although the eigenstates $|\psi_m\rangle$ and $|\psi_n\rangle$ in Eq. (14) depend on the geomagnetic field direction, this dependence could be rather weak, particularly when averaging over all eigenstates. This result is verified by our numerical calculations [see [22] regarding $\sum_\alpha \mathcal{S}_\alpha(\omega)$]. Figure 3(b) shows the singlet fidelity of the radical pair when the three triplets are degenerate. The MagR spins cause a remarkable transition from the singlet state to the triplet states. However, the sensitivity to the field direction is significantly reduced [see Fig. 3(d)]. In sharp contrast, the nondegenerate case shows a strong magnetosensation ability [see Fig. 3(c)].

Incoherent effect.—Thus far, we have focused on the coherent dynamics of the radical pair spins and the MagR

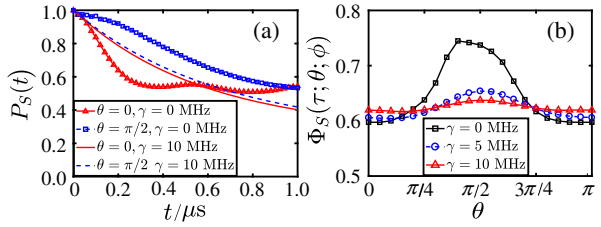

FIG. 4. (a) The singlet fidelity for different relaxation and dephasing rates γ for different geomagnetic field directions. (b) The singlet productivity as a function of the geomagnetic field direction θ for different relaxation and dephasing rates.

spins. However, since the whole magnetosensation system is inevitably subjected to a biological environment (mainly via the electron-phonon interactions at the room temperature), environment-induced decoherence must be considered. Accordingly, we include the relaxation and decoherence of the MagR bath spins, which are governed by the Lindblad equation

$$\dot{\rho} = -i[H,\rho] + \sum_{i=1}^{3N} \gamma_i \left\{ \hat{D}_i^\dagger \rho \hat{D}_i - \frac{1}{2}\hat{D}_i^\dagger \hat{D}_i \rho - \frac{1}{2}\rho \hat{D}_i^\dagger \hat{D}_i \right\}, \tag{15}$$

where $\hat{D}_i = \sigma_i^{(z)}$ and $\sigma_i^{(\pm)}$ (the Pauli matrices) for spin dephasing and spin relaxation processes, respectively, and γ_i represents the corresponding relaxation and dephasing rates [36,37]. For simplicity, we set $\gamma_i \equiv \gamma$ for all of the MagR spins. Figure 4(a) compares the singlet fidelity with and without the effect of environmental decoherence. With the decoherence process described in Eq. (15), the radical pair can still undergo a singlet-triplet transition. However, the geomagnetic field direction sensitivity is significantly reduced in an environment with strong decoherence, as shown in Fig. 4(b). In this sense, the result indicates that the quantum coherence within the MagR is crucial to the biocompass.

Conclusion.—In summary, we establish a microscopic model of the magnetic-protein-assisted biocompass and analyze the physical origin of the magnetosensation. With quantum mechanical calculations, we show that the magnetosensation of the radical pair is the consequence of the magnetic fluctuation of the MagR rather than the mean magnetization. Furthermore, we discover that microscopic spin coupling and the level structure of the MagR and radical pair spins are essential to the magnetosensation. We propose two general necessary conditions, a resonance condition and a nondegeneracy condition, for the biocompass. These conditions provide more quantitative criteria for candidate biocompass systems and can be examined in future biophysical experiments at the molecular level with well-developed experimental electron spin resonance and nuclear magnetic resonance techniques. We also find that quantum coherence plays an important role in the geomagnetic field navigation process. This finding could inspire studies of various quantum effects in biological systems and bionic applications of artificial quantum systems.

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