The quantum Zeno effect immunizes the avian compass against the deleterious effects of exchange and dipolar interactions

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ARTICLE INFO

ABSTRACT

Magnetic-sensitive radical-ion-pair reactions are understood to underlie the biochemical magnetic compass used by avian species for navigation. Recent experiments have provided growing evidence for the radical-ion-pair magnetoreception mechanism, while recent theoretical advances have unravelled the quantum nature of radical-ion-pair reactions, which were shown to manifest a host of quantum-information-science concepts and effects, like quantum measurement, quantum jumps and the quantum Zeno effect. We here show that the quantum Zeno effect provides for the robustness of the avian compass mechanism, and immunizes its magnetic and angular sensitivity against the deleterious and molecule-specific exchange and dipolar interactions.

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1. Introduction

"In the history of natural selection, did nature ever come across a way to use quantum weirdness?" This is a question claimed (Lloyd, 2009) to have an affirmative answer, at least in regard with the apparent ability of photosynthetic antennae to efficiently guide the excitonic energy to the photosynthetic reaction center. Questions like the previous one, addressing the possibility of biological processes exhibiting non-trivial quantum effects, ordinarily thought to be suppressed in the decoherence-prone biological environment (Davies, 2004; Abbott et al., 2008), have attracted an increasing attention in recent years. For example, significant experimental (Engel et al., 2007; Lee et al., 2007) and theoretical (Plenio and Huelga, 2008; Mohseni et al., 2008) progress has been recently made on elucidating the role of quantum coherence and quantum walks, respectively, in the workings of photosynthetic antennae complexes. In a different front, radical-ion-pair reactions (Schulten, 1982; Steiner and Ulrich, 1989) have been recently shown (Kominis, 2009, 2011; Jones and Hore, 2010; Katsoprinakis et al., 2010; Cai et al., 2010; Gauger et al., 2011; Cai, 2011) to exhibit the full machinery of concepts and physical effects familiar from quantum information science. Radical-ion pairs play a fundamental role in a series of biologically relevant chemical reactions, ranging from charge transfer initiated reactions in photosynthetic reaction centers (Boxer et al., 1983) to magnetic sensitive reactions abounding in the field of spin-chemistry (Timmel et al., 1998,

2001; Timmel and Henbest, 2004). In particular, radical-ion pairs are understood to underlie the biochemical magnetic compass used by avian species to navigate in earth's magnetic field (Ritz et al., 2000; Wiltschko and Wiltschko, 2005), as corroborated by several recent experiments (Ritz et al., 2004, 2009; Maeda et al., 2008; Zapka et al., 2009).

In Fig. 1 we depict a generic model for radical-ion-pair reactions, which form a magnetic sensor since the reaction product yields depend on the external magnetic field. Radical-ion pairs are formed by a charge transfer process following a photoexcitation of a donor–acceptor dyad, leading to two molecular ions and two unpaired electrons. The latter can either be in the spin singlet or in the spin triplet state. Magnetic interactions with the external magnetic field and hyperfine interactions with the molecule's magnetic nuclei bring about a coherent singlet–triplet oscillation. At some random instant in time the reaction is terminated, since the radical-ion-pair undergoes charge recombination, leading to the reaction products. Angular momentum conservation enforces spin selectivity of the recombination process, i.e. singlet (triplet) radical-ion pairs recombine to singlet (triplet) neutral products. Moreover, anisotropic hyperfine interactions within the molecule render the reaction yields dependent on the inclination of the external magnetic field with respect to a molecule-fixed coordinate frame.

Interestingly, intra-molecule magnetic interactions are more complicated. Both spin-exchange and long-range dipolar interactions affect reaction dynamics, to an extent dependent on the particular molecular structure. In this respect, it has been recently shown (Efimova and Hore, 2008) that the presence of exchange and/or dipolar interactions significantly suppresses the magnetic and angular sensitivity of the reaction yields, thus severely

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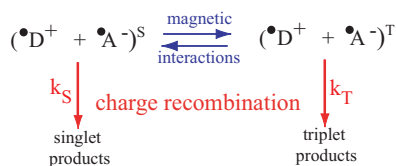   E-mail address: ikominis@iesl.forth.gr (I.K. Kominis).

Fig. 1. Radical-ion-pair reaction dynamics: photoexcitation of a donor–acceptor molecule DA followed by charge-transfer creates a radical-ion-pair, i.e. two molecular ions and two unpaired electrons (two dots). The Zeeman interaction of the two unpaired electrons with the external magnetic field and hyperfine interactions with the molecule's magnetic nuclei induce a coherent singlet–triplet conversion, ceased by the spin-selective charge recombination, which transforms singlet (triplet) radical-ion pairs into singlet (triplet) neutral products at a rate k_S (k_T).

degrading the mechanism's functionality. Along the same lines, it was concluded (Efimova and Hore, 2008) that only when the molecular parameters determining J and D, the exchange and dipolar couplings, are fine-tuned so that the effects of these two interactions cancel each other, is the magnetic and angular sensitivity of the reaction restored. Although it is conceivable that nature has conjured up such a fortuitous cancellation for a functionally important biological sensor, the fact that J and D depend sensitively on molecule-specific parameters, like the donor–acceptor distance r (for example J has an exponential dependence on r) makes this possibility questionable.

It was recently shown (Kominis, 2009) that radical-ion-pair reactions form a biochemical system that exhibits the quantum Zeno effect (Misra and Sudarshan, 1977; Itano et al., 1990; Facchi and Pascazio, 2001; Koshino and Shimizu, 2005; Kofman and Kurizki, 2000). We will here show that when the quantum Zeno effect is manifested (i.e. when the recombination rates are asymmetric), the reaction's magnetic and angular sensitivity is practically independent of the presence or not of exchange and/or dipolar interactions. This realization has profound implications for the robustness of this biological sensor, i.e. a non-trivial quantum effect renders the sensor insensitive to molecule-specific parameters (Efimova and Hore, 2008), such as donor–acceptor distance (affecting the exchange coupling and the long-range dipolar coupling) and the inter-radical medium and the particular electronic structure (affecting the exchange coupling). Whether nature has engineered molecules realizing a fine-tuned cancellation (Efimova and Hore, 2008) of the adverse effects of exchange and dipolar interactions, or on the other hand, has evolved the avian compass into operating at the quantum Zeno regime, remains to be discovered. In the following we will analyze the merits of the latter possibility. It is noted that the topic of this work is at the center of two debates. The first has to do with whether the avian magnetoreception is based on the radical-pair mechanism or magnetic nano-particles, as suggested by several authors (Kirschvink et al., 2001; Kirschvink and Gould, 1981; Johnsen and Lohmann, 2005; Solovyov and Greiner, 2007; Semm and Beason, 1990). We do not make any suggestion as to which mechanism is actually responsible for avian magnetic navigation. We just deal with a particular weakness of the radical-pair magnetoreception as described in Efimova and Hore (2008) and suggest how the radical-pair magnetoreception can be indeed viable in the appropriate parameter regime. The second debate has to do with the fundamental master equation describing radical-ion-pair reactions (Kominis, 2009, 2011, 2011; Jones and Hore, 2010; Jones et al., 2011, 2011; Ivanov et al., 2010). In particular, there are currently three different theories describing the quantum dynamics of these reactions, the traditional theory (also referred to as Haberkorn master equation), the Jones-Hore theory and the theory developed by one of us. As will be shown in the following, the results of this work are qualitatively valid for all three theories, the only differences being quantitative.

In Section 2 we reiterate the quantum dynamics of radical-ion-pair reactions and elaborate on the magnetic interactions within the radical-ion-pair central to the problem of study. In Section 3 we analyze the magnetic and angular precision of the avian compass magnetic sensor in the presence of exchange interactions, while in Section 4 we explain the robust performance of the avian compass as a direct consequence of the quantum Zeno effect and the spin delocalization resulting from the quantum measurement dynamics inherent in radical-ion-pair recombination reactions.

2. Quantum Dynamics and Magnetic Interactions in the Radical-ion-pair Avian Compass

What is of interest in describing radical-ion-pair reactions is the spin state of the pertaining particles, the two electrons and the molecule's nuclear spins. The spin state of the radical-ion-pair is described by a $4n$-dimensional density matrix ρ, where the factor 4 is the spin multiplicity of the two electrons and $n = (2I_1 + 1)(2I_2 + 1)$ ... $(2I_k + 1)$ is the nuclear spin multiplicity of the molecule's k nuclei having nuclear spins $I_1, I_2, \ldots, I_k$. The time evolution of ρ is described by a master equation of the form

$$\frac{d\rho}{dt} = -i[\mathcal{H}_m, \rho] - \mathcal{L}(\rho) \tag{1}$$

where the first term describes the unitary evolution of ρ due to the magnetic interactions embodied in $\mathcal{H}_m$ and $\mathcal{L}$ denotes a superoperator that takes into account the reaction dynamics. It is this part of the theoretical description that the three above mentioned theories differ, and the relevant details can be found in the recent literature (Kominis, 2009, 2011; Jones and Hore, 2010). The two basic parameters and operators that determine the reaction dynamics are the singlet and triplet recombination rates k_S and k_T, and the singlet and triplet projection operators, Q_S and Q_T, respectively. Once the density matrix evolution is known, i.e. once the master equation (1) is solved, the reaction yield, e.g. the triplet can be calculated from

$$Y_T = k_T \int_0^\infty \text{Tr}\{\rho Q_T\} \tag{2}$$

The magnetic Hamiltonian for the problem under study, $\mathcal{H}_m = \mathcal{H}_Z + \mathcal{H}_{hf} + \mathcal{H}_{ex}$, is composed of $\mathcal{H}_Z$, the Zeeman interaction of the two unpaired electrons (nuclear Zeeman interaction is negligible) with the external magnetic field, $\mathcal{H}_{hf}$, the hyperfine couplings of the electrons with the surrounding nuclear spins, and finally the spin-exchange interaction, $\mathcal{H}_{ex}$. For the transparency of the following discussion we will ignore the dipolar interaction as its inclusion leads to exactly the same conclusions. The Zeeman interaction Hamiltonian that will be used for the study of the magnetic sensitivity is $\mathcal{H}_{Z,magn} = \omega(s_{1z} + s_{2z})$, where the magnetic field of magnitude B is assumed to be in the z-axis ($\omega = \gamma B$, with $\gamma = 2\pi \times 2.8$ MHz/G). For the study of the angular sensitivity we take the magnetic field, again of magnitude B, to be in the x–y plane, hence the Zeeman interaction term will be $\mathcal{H}_{Z,ang} = \omega \cos \phi(s_{1x} + s_{2x}) + \omega \sin \phi(s_{1y} + s_{2y})$. For the study of the magnetic sensitivity we vary B, whereas for studying angular sensitivity we keep B constant and vary the angle ϕ. In the following we will consider the simplest physically realizable radical-ion-pair containing just one spin-1/2 nucleus (in which case dim(ρ)=8), hence the hyperfine interaction Hamiltonian is $\mathcal{H}_{hf} = \mathbf{I} \cdot \mathbf{A} \cdot \mathbf{s}_1$, where $\mathbf{A}$ is the hyperfine coupling tensor of the single nuclear spin $\mathbf{I}$ existing in e.g. the donor molecule with the donor's unpaired electron. We will consider the simplest case where the hyperfine tensor is diagonal with one non-zero component $A_{xx} = a$, to provide for the angular sensitivity on the x-y plane. Thus $\mathcal{H}_{hf} = a s_{1x} I_x$. Finally the spin-exchange Hamiltonian is $\mathcal{H}_{ex} = J \mathbf{s}_1 \cdot \mathbf{s}_2$. We note that the simplification of considering just one nuclear spin is common in all such considerations, and although it does not exhaust all the richness of phenomena that can be

observed by the realistic inclusion of more nuclear spins (as is the case in nature), it does provide an idea of what is in principle feasible, and this is exactly the goal of this work.

In the following we will calculate the magnetic and angular sensitivity of the reaction for two regimes: (i) the "traditional" regime with equal recombination rates $k_S = k_T$ on the order of or smaller than the hyperfine coupling a. It is in this regime that almost all calculations have been performed based on the previous, traditional master equation. We then study the regime (ii) where $k_T \gg k_S$ with k_T on the order of or larger than the hyperfine coupling a, i.e. when the quantum Zeno effect is manifested. To elaborate on this, we note that if the initial state of the molecule is the singlet (which is usually the case) and there exist asymmetric recombination rates then the spin state of the radical-pair is strongly projected to the singlet state by the triplet reservoir. As has been explained in Kominis (2009, 2011), the singlet and triplet reservoirs essentially measure the observable Q_S at a total measurement rate of $(k_S + k_T)/2$. A large measurement rate essentially means frequent quantum jumps to either the singlet or the triplet state. Since the molecule starts out from the singlet, chances are that most of those jumps will be to the singlet state, hence the strong projection to the singlet, which is the signature of the quantum Zeno effect, or in other words, the strong measurement regime (the same considerations obviously apply to the case of a triplet initial state and $k_S \gg k_T$). We will then show that in the regime (i) the inclusion of the spin exchange interaction indeed degrades the magnetic and angular sensitivity of the reaction, as has already been analyzed (Efimova and Hore, 2008). However, regime (ii) exhibits an appreciable magnetic and angular sensitivity with their dependence on the exchange coupling J being significantly suppressed.

3. Magnetic and Angular Sensitivity of the Avian Compass

In Fig. 2a and b we plot an example of the triplet reaction yield Y_T, calculated from (2), as a function of the external magnetic field (using $\mathcal{H}_{Z,magn}$) and the field's angle (using $\mathcal{H}_{Z,ang}$), respectively. The magnetic sensitivity of the reaction at earth's field of interest for the avian compass is proportional to the slope of Y_T vs B calculated at $B = 0.5$ G. Similarly, the angular sensitivity of the reaction is proportional to the (maximum) slope of Y_T vs ϕ. The smallest measurable change of the magnetic field, δB (absolute magnetic sensitivity), and the smallest detectable change, $\delta\phi$, in the field's angle with respect to the molecule's x-axis (absolute angular sensitivity or heading error) both follow from the previous calculations if the smallest measurable reaction yield change, δY_T, is known. It thus follows that

$$\delta B = \frac{\delta Y_T}{|dY_T/dB|_{B=0.5\,G}} \tag{3}$$

$$\delta\phi = \frac{\delta Y_T}{(Y_{T,max} - Y_{T,min})/\Delta\phi} \tag{4}$$

where $Y_{T,min}$ and $Y_{T,max}$ are the minimum and maximum values of the yield $Y_T(\phi)$ and $\Delta\phi = 90°$ is the angular width of the full swing between $Y_{T,min}$ and $Y_{T,max}$. To make further progress the value of δY_T must be known or estimated. Obviously δY_T depends on the particular realization of the biochemical mechanism transducing the radical-ion-pair reaction yield to a physiological signal. On rather general grounds it has been shown (Weaver et al., 2000) that δY_T is connected to N_R, the number of neuronal receptors sensitive to the radical-ion-pair reaction product molecules, by $(\delta Y_T)^2 = 4/N_R$. We choose $N_R = 1.6 \times 10^7$, in order to set δY_T at the value $\delta Y_T = 0.05\%$. The chosen value of N_R and hence δY_T is realistic (Weaver et al., 2000) and has the consequence that it sets the magnetic sensitivity at zero exchange coupling at the value of $\delta B \approx 0.01$ G, i.e. at 2% of earth's field. This level of magnetic sensitivity is understood
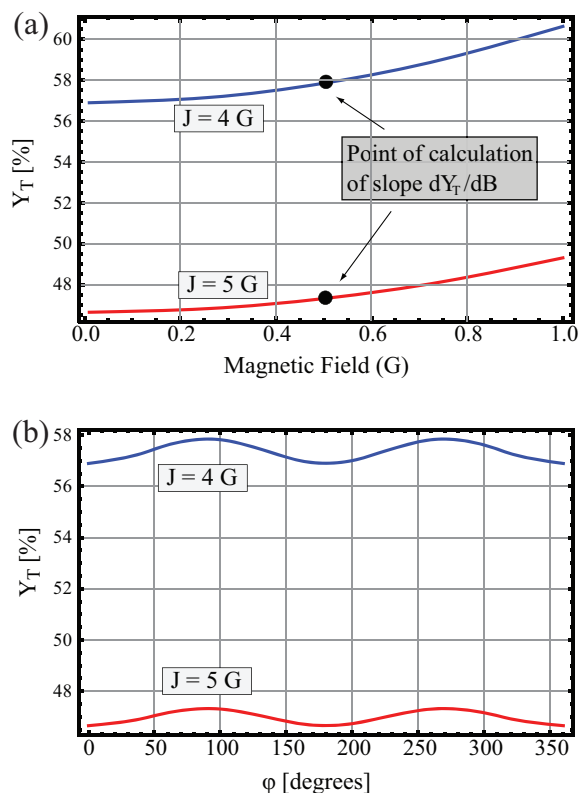

Fig. 2. Examples of (a) magnetic and (b) angular sensitivity of the triplet reaction yield as a function of (a) magnetic field and (b) magnetic field's direction in the horizontal plane for two different values of the exchange coupling J. The calculations were done for $k_S = 0.5$ MHz, $k_T = 40$ MHz, hyperfine coupling $a = 1.75$ G and a magnetic field $B = 0.5$ G for the angular sensitivity.

(Wiltschko and Wiltschko, 2005) to be actually realized in several avian species. It is stressed, however, that the following considerations are qualitatively independent of the particular value of δY_T, which just sets the absolute scale of the derived magnetic and angular sensitivity.

From plots like the ones in Fig. 2a and b, and for various values of the exchange coupling J, we obtain the sensitivities δB and $\delta\phi$, according to (3) and (4), which are plotted in Fig. 3a and b, respectively. It is clearly seen in Fig. 3a that in the traditional regime (i) the magnetic precision plunges to $\delta B = 0.5$ G already at $J \approx 6$ G. Similarly, as shown in Fig. 3b, the angular precision in regime (i) drops dramatically with increasing J, with a complete loss of heading information already at $J = 6$ G. In contrast, in the quantum Zeno regime (ii) the angular precision of about $\delta\phi = 40°$ at the highest value of the exchange coupling is actually at the level of experimental observations (Wiltschko and Wiltschko, 1996; Cochran et al., 2004) of the heading error of the avian compass. Finally, as noted before, all three theories produce qualitatively similar results. The particular values obtained here for the absolute sensitivities δB and $\delta\phi$ obviously depend on the particular hyperfine couplings used and the chosen values of the recombination rates. As pointed out in Section 1, more complicated models will result in different numbers, however, our sole goal is to demonstrate a behavior that is in principle feasible.

4. Explanation of the Robust Avian Compass Sensitivity

We will now explain the robust magnetic and angular sensitivity resulting in the quantum Zeno regime. This follows by considering
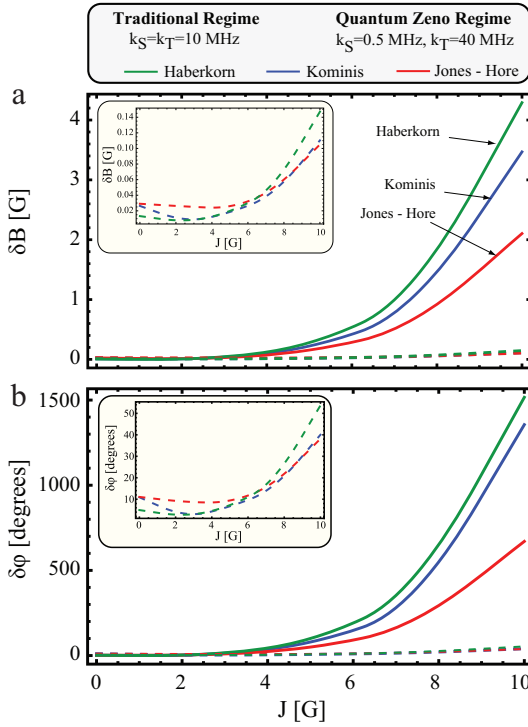
Fig. 3. (a) Magnetic sensitivity and (b) angular sensitivity (heading error) of the reaction as a function of the exchange coupling J for the two different regimes of (i) equal recombination rates (solid lines) and (ii) asymmetric recombination rates (dashed lines) and for all three theories. Insets zoom into low δB and $\delta\phi$ values in order to make the predictions of all three theories in regime (ii) distinguishable. For all calculations $k_S = k_T = 10$ MHz for the traditional regime, $k_S = 0.5$ MHz and $k_T = 40$ MHz for the Zeno regime and $a = 1.75$ G. For the angular sensitivity calculation the magnitude of the magnetic field was $B = 0.5$ G. It is obvious that both the magnetic and the angular sensitivity depend on J much less sensitively in regime (ii), where the strong projective measurement induced by a large k_T (quantum Zeno effect) dominates the dynamics.

the behavior of unrecombined radical-ion pairs, described by the master equation

$$\frac{d\rho}{dt} = -i[\mathcal{H}_m, \rho] - \frac{(k_S + k_T)(Q_S\rho + \rho Q_S - 2Q_S\rho Q_S)}{2} \quad (5)$$

This master equation has been derived in Kominis (2009) and its physical meaning explained in detail in Kominis (2011). Essentially, unrecombined radical-ion pairs suffer a loss of singlet–triplet coherence due to the continuous measurement of Q_S induced by the singlet and triplet reservoirs and the concomitant quantum jumps. To get an insight into the dynamics in the regime of the asymmetric recombination rates, we consider the eigenvalues of the master equation (5), which are obtained by diagonalizing the matrix $\mathcal{M}$ (of dimension $\dim(\rho)^2$) that satisfies $d\tilde{\rho}/dt = \mathcal{M}\tilde{\rho}$, where $\tilde{\rho}$ is a column matrix containing all matrix elements of ρ. The resulting eigenvalues are of the form $-\lambda + i\Omega$, with $\lambda \geq 0$ being the decay rate and Ω the oscillation frequency of the particular eigenmode. As is in general the case with the quantum Zeno effect (Streed et al., 2006), some of the eigenvalues have decay rates increasing with the measurement rate k as $\lambda \sim k$, while the others (responsible for the quantum Zeno effect) decrease with k as $\lambda_{qZ} \sim h^2/k$, where h is the characteristic frequency scale of the system, here determined by the magnetic Hamiltonian $\mathcal{H}_m$. In our case, the measurement rate $k = (k_S + k_T)/2$, and in the quantum Zeno regime in which $k_T \gg k_S$, it will be $k \approx k_T/2$.

Now, the exchange Hamiltonian can be written (up to an additive constant) as $\mathcal{H}_{ex} = -JQ_S$. Furthermore, as is known from quantum measurement theory (Breuer and Petruccione, 2002), the deterministic evolution of the system's quantum state (due to the
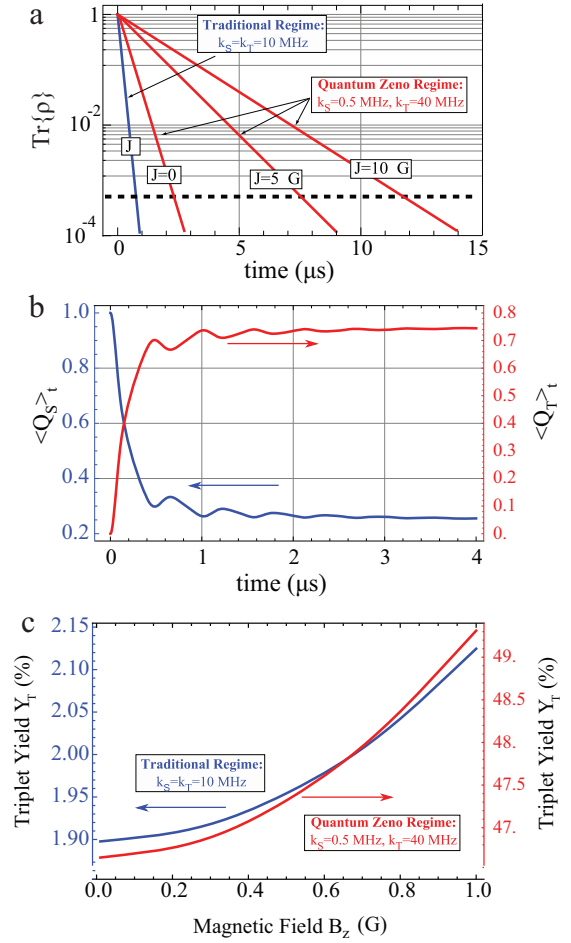

Fig. 4. (a) Time evolution of the normalization of ρ. The dashed line at $N = 5 \times 10^{-4}$ signifies the "termination" of the reaction, i.e. the point when the remaining radical-ion pairs are 0.05% of the initial number. It is seen that in the quantum Zeno regime, the reaction lasts longer for increasing J, as explained in the text. In contrast, in the traditional regime of equal recombination rates the duration of the reaction is independent of J. (b) Time evolution of the singlet and triplet probability, $\langle Q_S(t)\rangle$ and $\langle Q_T(t)\rangle$, respectively for the unrecombined radical-pairs, calculated from (5) for $B = 0.5$ G and $J = 10$ G. The measurement dynamics inherent in the charge recombination process of radical-ion pairs "delocalize" the electron spin state at long times. (c) Triplet yield as a function of the magnetic field for $J = 10$ G, plotted in the two regimes for the recombination rates.

unitary Hamiltonian evolution and the measurement of Q_S with rate k) is generated by the non-hermitian operator $\mathcal{K} = \mathcal{H}_m - ikQ_S$. It is easily seen that if $\mathcal{H}_m^{J=0}$ is the magnetic Hamiltonian without the exchange interaction $\mathcal{H}_{ex}$, then $\mathcal{K} = \mathcal{H}_m^{J=0} - i(k - iJ)Q_S$, i.e. the inclusion of the exchange interaction is equivalent to replacing k with an imaginary measurement rate $k - iJ$. We can now complete the argument as follows: the eigenvalues with a real part that scales as $\lambda \sim k$ pick up an oscillation frequency (in addition to Ω) of $-J$, the effect of which roughly averages out. On the other hand, the eigenvalues with the quantum Zeno scaling $\lambda_{qZ} \sim h^2/k$ suffer a change in their real part which becomes (since in our case $k/J < 1$) $\lambda'_{qZ} \approx h^2 k/J^2 \ll \lambda_{qZ}$. Thus, with increasing J, the spin state evolution is slowed down. This can be clearly seen in Fig. 4a, which shows the time evolution of the normalization of the density matrix, $\text{Tr}\{\rho\}$, i.e. the number of existing radical-ion pairs, as calculated from (1). The reaction is considered to be terminated when $\text{Tr}\{\rho\} \approx 5 \times 10^{-4}$, i.e. when the reaction yield is known to within δY_T. It is clearly seen that in the quantum Zeno regime, the reaction time depends on J in the way outlined before. On the contrary, when $k_S = k_T = \kappa$, the change of $\text{Tr}\{\rho\}$ during the time interval dt easily follows from (1)

and is $d\mathrm{Tr}\{\rho\} = -dt(k_S\langle Q_S\rangle + k_T\langle Q_T\rangle) = -\kappa dt\mathrm{Tr}\{\rho\}$, since $Q_S + Q_T = 1$. Hence the reaction time is proportional to $1/\kappa$ and independent of J. The result is that during the short reaction time in the traditional regime, the triplet probability Q_T has not increased appreciably (Fig. 4b), and the triplet yield is small, as shown in Fig. 4c. In contrast, in the quantum Zeno regime the reaction has enough time to "sample" large values of Q_T and lead to a triplet yield about an order of magnitude higher, hence the higher sensitivity in this regime. In other words, as seen in Fig. 4c, the relative change $\delta Y_T/Y_T$ of the triplet yield with the magnetic field is roughly the same in both cases, but the absolute value of Y_T differs by a factor of 20, leading to respectively high slopes dY_T/dB and $dY_T/d\phi$. To summarize, the quantum measurement dynamics inherent in the recombination process of radical-ion pairs result in "delocalization" of the electron spin state at long times, as evidenced in Fig. 4b. The asymmetric ($k_T \gg k_S$) recombination rates result in the J-dependence of the reaction time. The interplay of these two effects provides for the robust magnetic and angular sensitivity in the presence of the exchange interaction.

4.1. Quantum Zeno Effect in the Traditional Master Equation

The quantum Zeno effect is embodied also in the traditional theory as well as the Jones-Hore theory. This has been mentioned in Ivanov et al. (2010) and analyzed in detail in Berdinskii and Yakunin (2008). We will here elucidate this using a simple two-dimensional example. Consider the density matrix $\rho = \begin{pmatrix} \rho_{SS} & \rho_{ST} \\ \rho_{TS} & \rho_{TT} \end{pmatrix}$ and a magnetic Hamiltonian of the form $\mathcal{H} = \begin{pmatrix} 0 & \omega \\ \omega & 0 \end{pmatrix}$. The projection operators are in this case $Q_S = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$ and $Q_T = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$. The traditional master equation, $d\rho/dt = -i[\mathcal{H},\rho] - k_S(Q_S\rho + \rho Q_S)/2 - k_T(Q_T\rho + \rho Q_T)/2$ is, assuming for simplicity that $k_S = 0$, equivalent to

$$\frac{d}{dt}\begin{pmatrix} \rho_{SS} \\ \rho_{ST} \\ \rho_{TS} \\ \rho_{TT} \end{pmatrix} = \begin{pmatrix} 0 & i\omega & -i\omega & 0 \\ i\omega & -k_T/2 & 0 & -i\omega \\ -i\omega & 0 & -k_T/2 & i\omega \\ 0 & -i\omega & i\omega & -k_T \end{pmatrix}\begin{pmatrix} \rho_{SS} \\ \rho_{ST} \\ \rho_{TS} \\ \rho_{TT} \end{pmatrix} \qquad (6)$$

The above 4×4 matrix has four eigenvalues, $-k_T/2$ (doubly degenerate), $-k_T/2 - \sqrt{k_T^2 - 16\omega^2}/2$ and $-k_T/2 + \sqrt{k_T^2 - 16\omega^2}/2$. For $k_T \gg \omega$, the last eigenvalue is approximately equal to $-2\omega^2/k_T$. This, as already noted, is the quantum Zeno scaling, i.e. the larger the interrogation rate k_T, the slower the decay of the density matrix elements dependent on the particular eigenvalue. In other words, even if the traditional theory is not constructed on the quantum measurement concepts on which our theory is based, being a successful phenomenological theory it does bear part of the physics entering radical-ion-pair reactions in the asymmetric recombination regime.

5. Conclusions

In conclusion, we have identified a concrete biological process in which fundamental quantum effects have a profound effect on the system's performance, alluding to the possibility that this biological quantum sensor has evolved to a robust device by taking advantage of non-trivial aspects of quantum physics. Coincidentally or not, it turns out (Daviso et al., 2009) that the radical-ion pairs participating in the last stages of the electron-transfer processes taking place in bacterial photosynthetic reaction centers operate at the quantum Zeno regime, i.e. the triplet recombination rate k_T is about 20 times larger than k_S, the singlet recombination rate. It is noted that the manifestation of the quantum Zeno effect does not require any parameter fine-tuning, but just the presence of asymmetric recombination rates. This regime seems to offer an operational advantage and hence the possibility that it is nature's inevitable choice is rather plausible.

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