State Transitions and Decoherence in the Avian Compass

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Quantum Biology

Does quantum mechanics play any role in biology?

↓

Quantum mechanics implicitly/covertly chemical reactions and bonding scheme of molecules

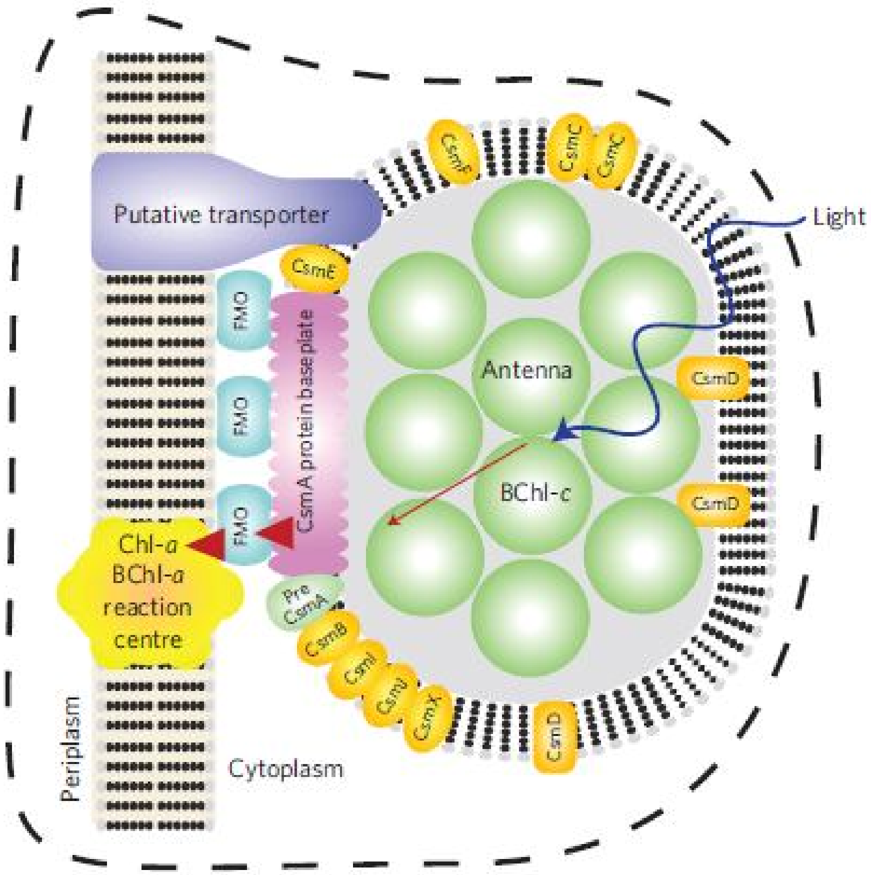
↓

‘Quantum biology’ is concerned with explicit/overt quantum mechanical effects in biological systems

Quantum Biological Systems

Photosynthesis Complex

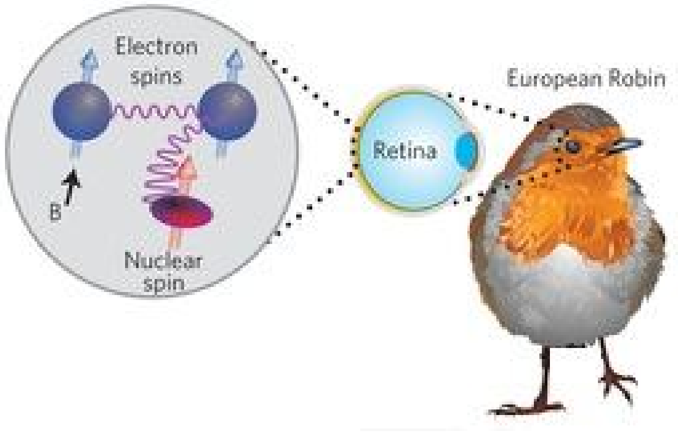
- Coherent excitonic transfer from antennae to reaction center
- Almost unity efficiency



Collini, Elisabetta, et al. "Coherently wired light-harvesting in photosynthetic marine algae at ambient temperature." *Nature* 463.7281 (2010): 644-647.

Quantum Biological Systems

- Avian Magnetoreception
  - Coherent radical pair spin dynamics responsible for geomagnetic field sense

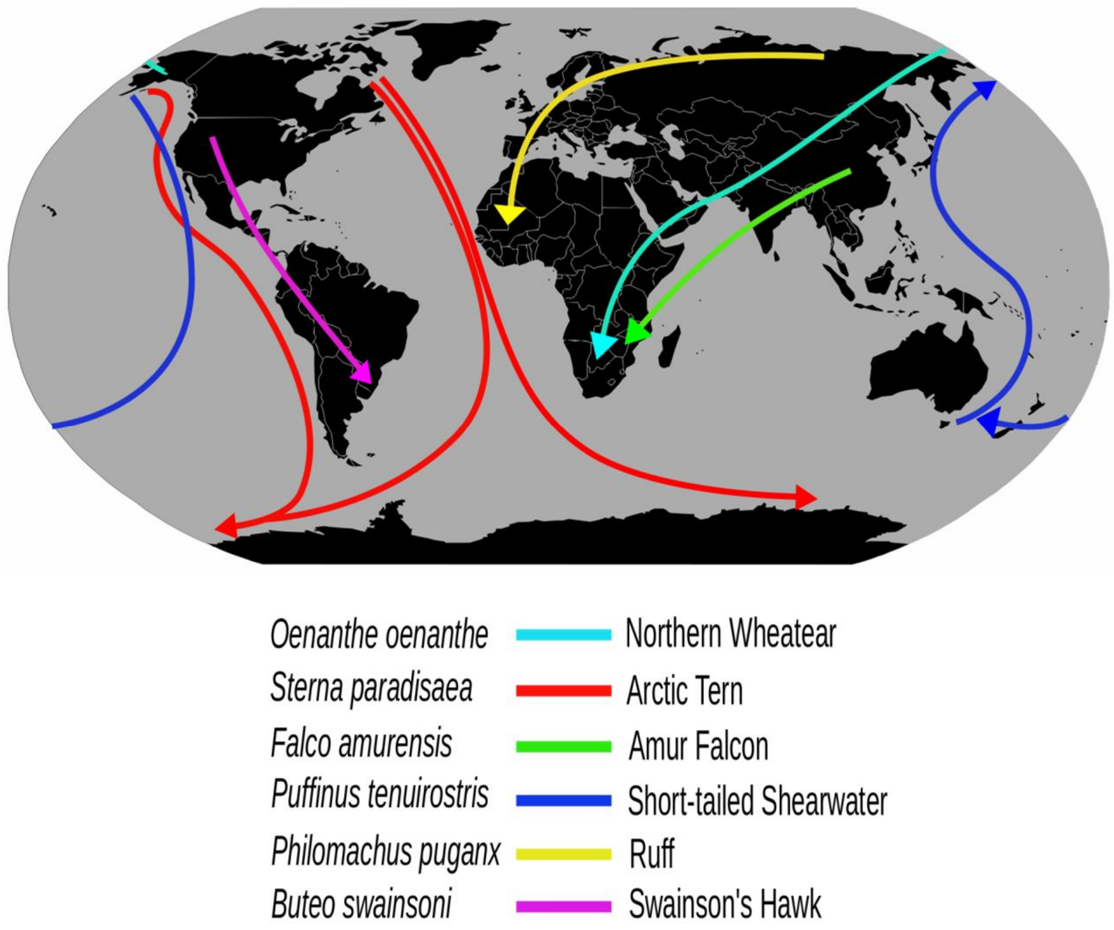


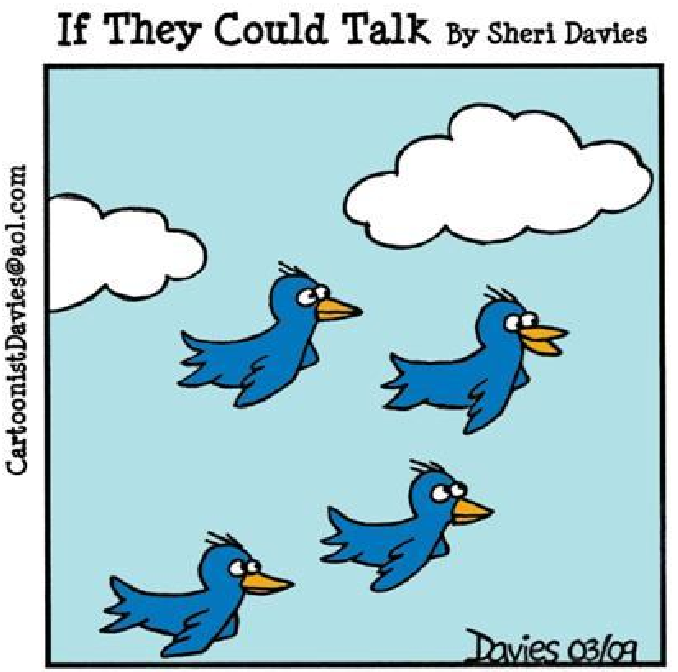
N. Lambert, et al. *Nature Physics* 2013

- Olfaction
  - Phonon assisted inelastic electron tunneling

- Enzyme Catalysis
  - Hydrogen tunneling

Avian Magnetoreception





"Last year at this time, we would've been headed north while relaxing in first class. In a way, I'm glad the economy forced us to go back to simpler times"

Avian Magnetoreception: Behavioral Characteristics

Behavioral experiments performed at Frankfurt.
Local geomagnetic field = 46 μT

- The avian compass is only polarity compass
  - No distinction between magnetic north and south

- Operational only in presence of certain range of optical frequencies

Avian Magnetoreception: Behavioral Characteristics

- Function Window
  - ± 30 % of the local geomagnetic field

- RF disruption
  - A weak (50 nT) transverse RF field (1.315 MHz) destroys the compass action

The Radical Pair Mechanism

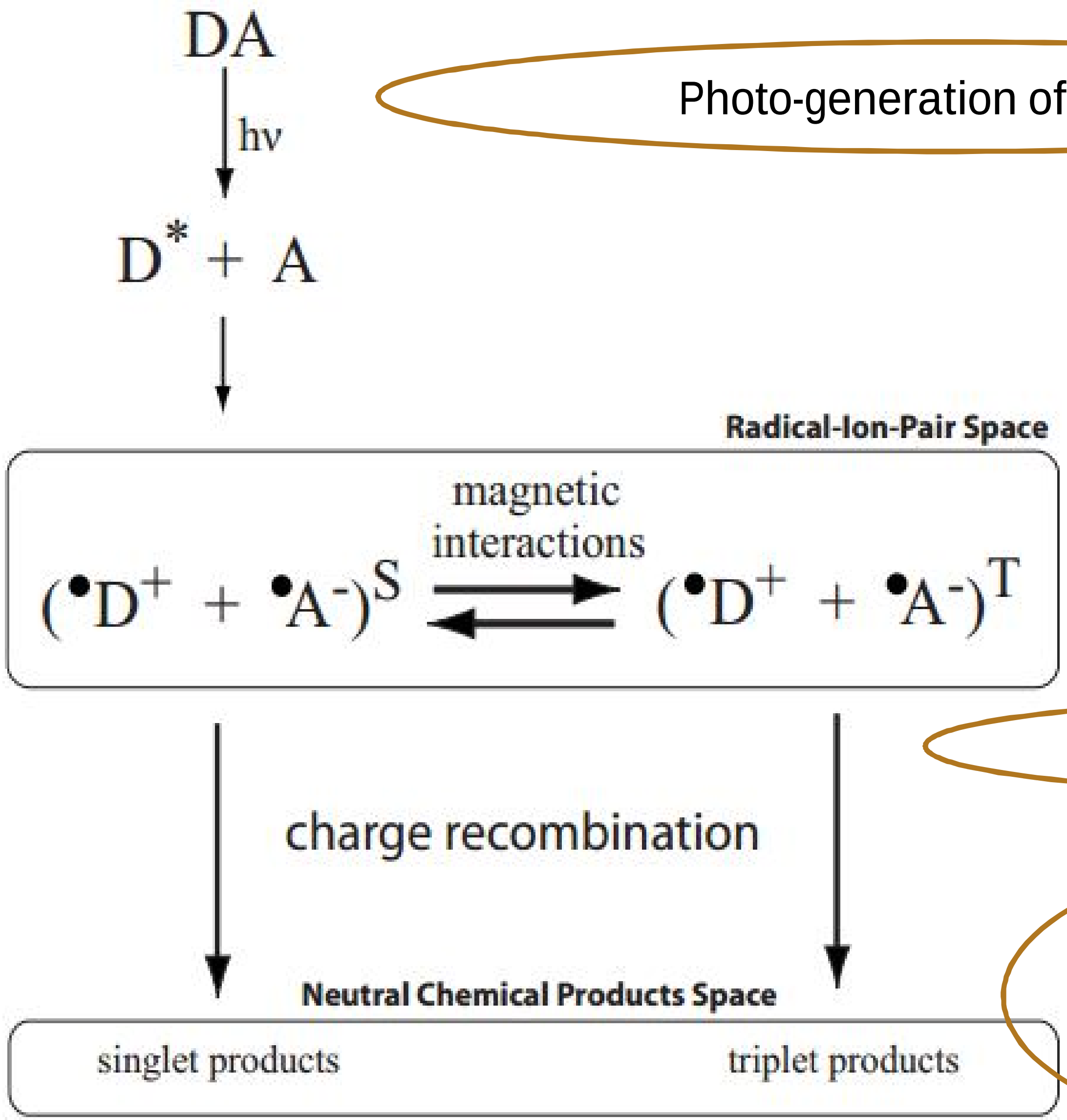


Photo-generation of radicals

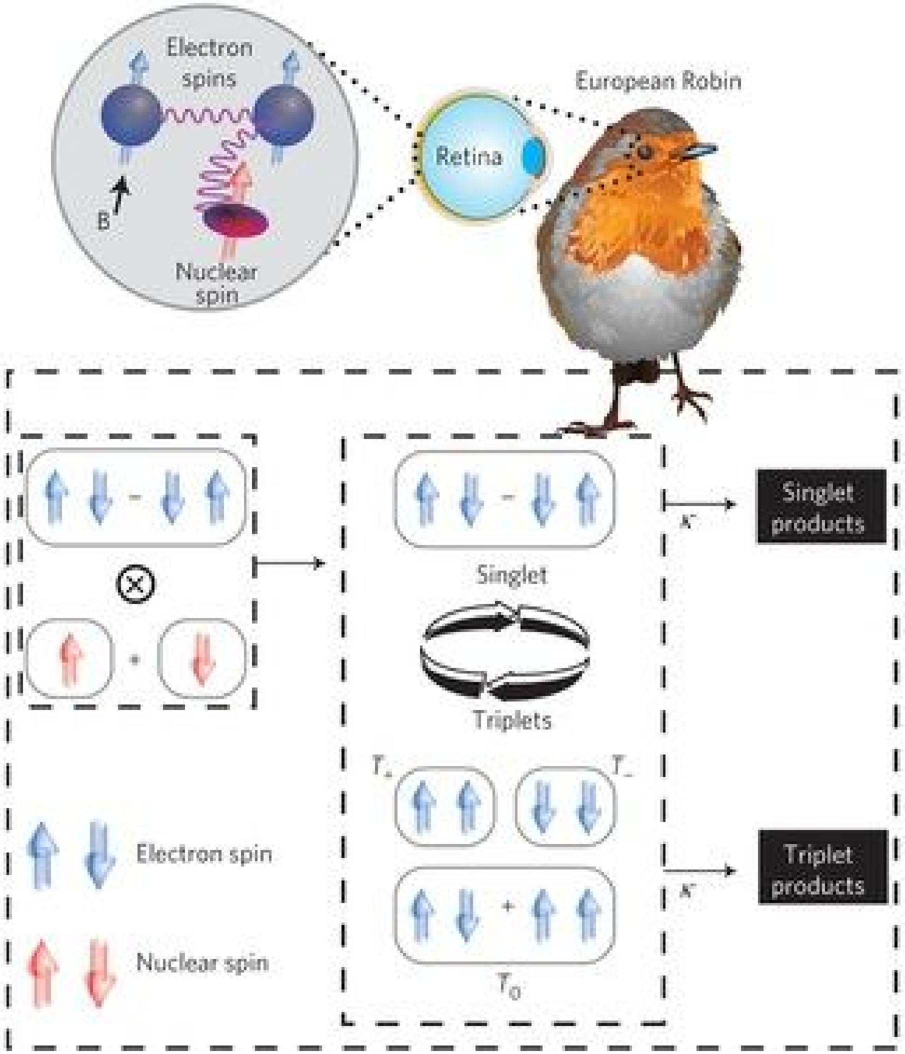
Spin state evolution of radical pair under local nuclear magnetic field and geomagnetic field

Radical pair recombination

The product depends on the spin state of radical pair just before recombination

Ritz, Adem, & Schulten, Biophys. J. 78, 707 (2000)

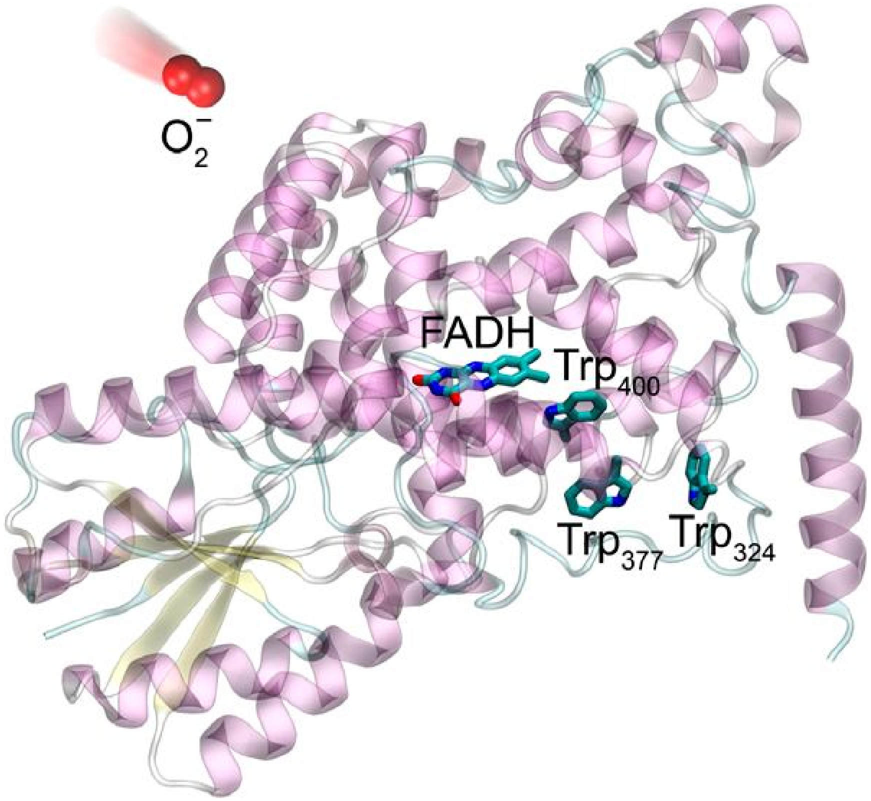
The Radical Pair Mechanism: Summary



N. Lambert, et al. *Nature Physics* 9.1, 10-18, 2013.

The Radical Pair Reaction

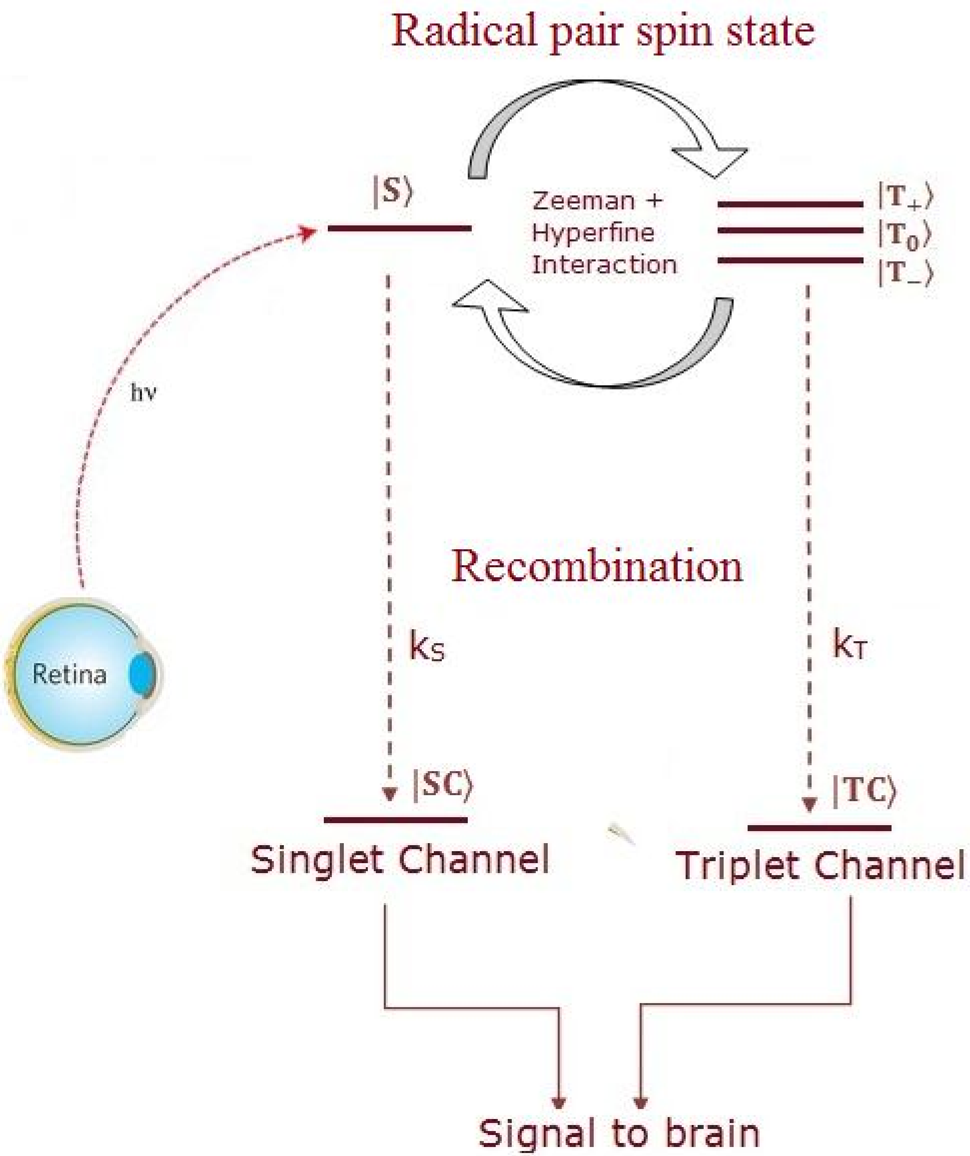
- Takes place in bird's retina



Cryptochrome

Solov'yov, Schulten, *SPIE Newsroom* (2009).

Spin Dynamics of the Radical Pair



- Radical pair spin state undergo intersystem crossing (singlet ←→ triplet)
- Recombination
- Define
  - Singlet Yield: Fraction of radical pairs recombining through singlet channel
  - Triplet Yield: Fraction of radical pairs recombining through triplet channel

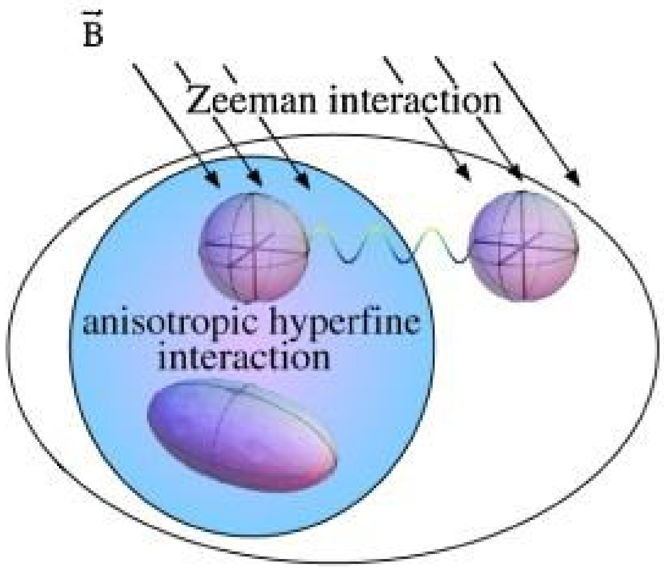
Theoretical Model: Hamiltonian

RF field (1.316 MHz) disruption of compass

⇩

One electron is free from hyperfine Interactions

⇩



E. M. Gauger, et al. PRL 106.4 2011.

Hamiltonian

$$H = \underbrace{\gamma \mathbf{B} \cdot (\hat{S}_1 + \hat{S}_2)}_{\text{Zeeman Interaction}} + \underbrace{\hat{I} \cdot \mathbf{A} \cdot \hat{S}_2}_{\text{Hyperfine Interaction}}$$

$$\mathbf{B} = B_0(\cos\varphi \sin\vartheta, \sin\varphi \sin\vartheta, \cos\vartheta)$$

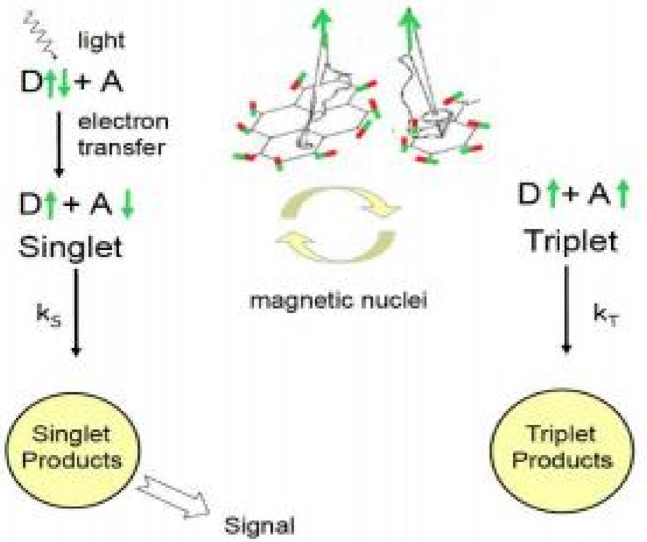
Theoretical Model: Dynamics

- RP System → Three spin system → 8 dims Hilbert space

- Consider the singlet and triplet channels as two more states

- Radical pair + Nucleus density matrix

$$\rho = [\rho_{nuc} \otimes \rho_{elec1} \otimes \rho_{elec2}] + 2\ recomb.channel\ states$$



Theoretical Model: Dynamics

- Phenomenological master equation for radical pairs

$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + k\sum_{i=1}^{8} P_i \rho P_i^\dagger - \frac{1}{2}(P_i^\dagger P_i \rho + \rho P_i^\dagger P_i)$$

$$P_1 = |SC\rangle\langle S\uparrow|$$
$$P_2 = |TC\rangle\langle T_0\uparrow|$$
$$P_3 = |TC\rangle\langle T_+\uparrow|$$
$$P_4 = |TC\rangle\langle T_-\uparrow|$$

And four similar operators corresponding to nuclear down spin states

- Initial State: $\rho(0) = \frac{1}{2}\mathbb{1}_N \otimes |S\rangle\langle S|$
  - Radical pair state is singlet state: $|S\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$
  - Nuclear state is completely mixed state

Some Earlier Results

PRL **106,** 040503 (2011) PHYSICAL REVIEW LETTERS week ending 28 JANUARY 2011

Sustained Quantum Coherence and Entanglement in the Avian Compass

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(Received 24 May 2010; revised manuscript received 23 November 2010; published 25 January 2011)

In artificial systems, quantum superposition and entanglement typically decay rapidly unless cryogenic temperatures are used. Could life have evolved to exploit such delicate phenomena? Certain migratory birds have the ability to sense very subtle variations in Earth's magnetic field. Here we apply quantum information theory and the widely accepted "radical pair" model to analyze recent experimental observations of the avian compass. We find that superposition and entanglement are sustained in this living system for at least tens of microseconds, exceeding the durations achieved in the best comparable man-made molecular systems. This conclusion is starkly at variance with the view that life is too "warm and wet" for such quantum phenomena to endure.

PRL **109,** 110502 (2012) PHYSICAL REVIEW LETTERS week ending 14 SEPTEMBER 2012

Quantum Coherence and Sensitivity of Avian Magnetoreception

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(Received 31 May 2012; published 14 September 2012)

Results: State Transitions

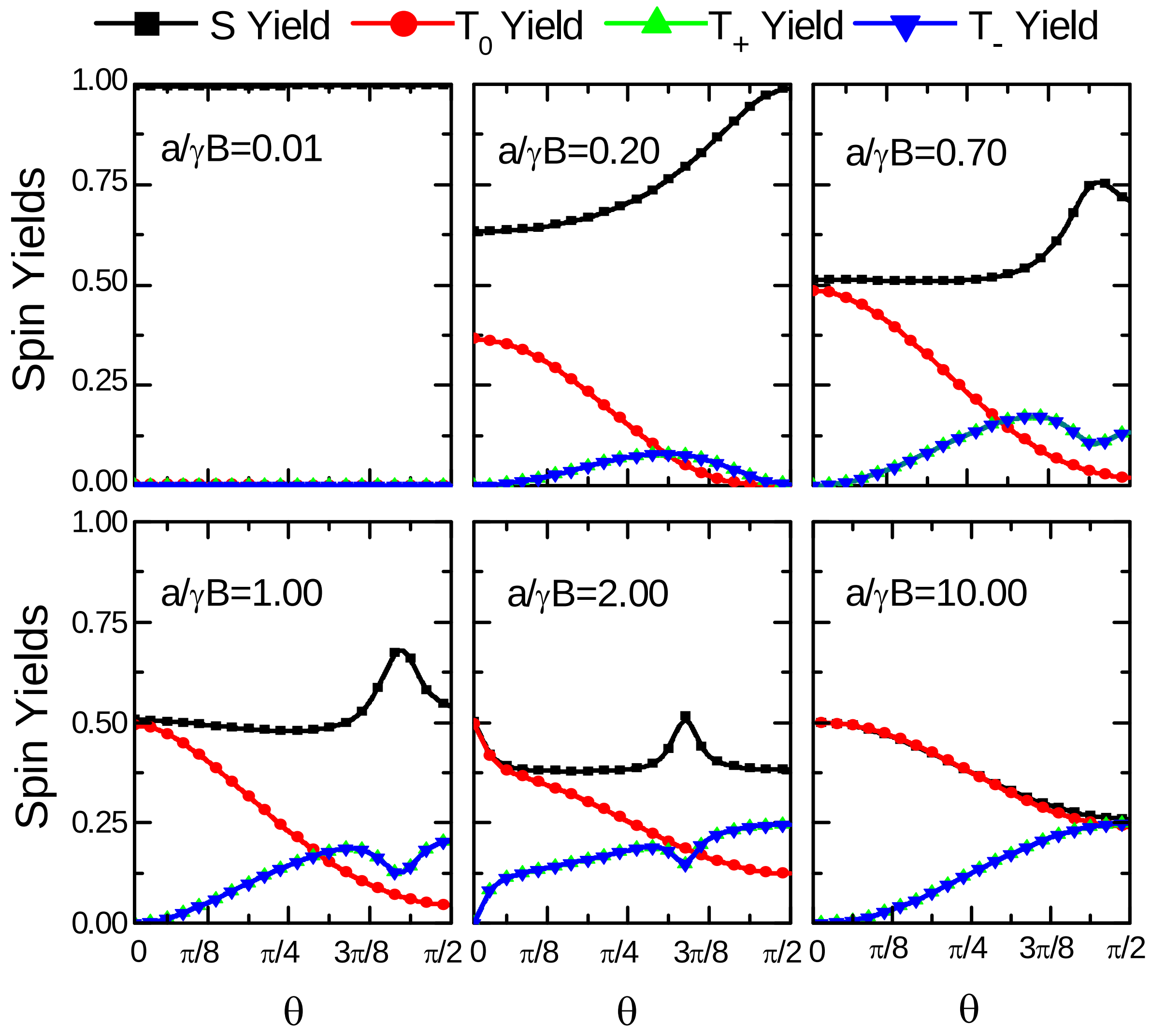
- The aim is to investigate the spin transitions involved in the radical pair model

- The transitions induced due to hyperfine and Zeeman interactions

- In order to achieve this, the singlet and triplet yields are calculated for a large number of hyperfine interactions strengths ($\gamma B_0/100$ to $100\gamma B_0$) for

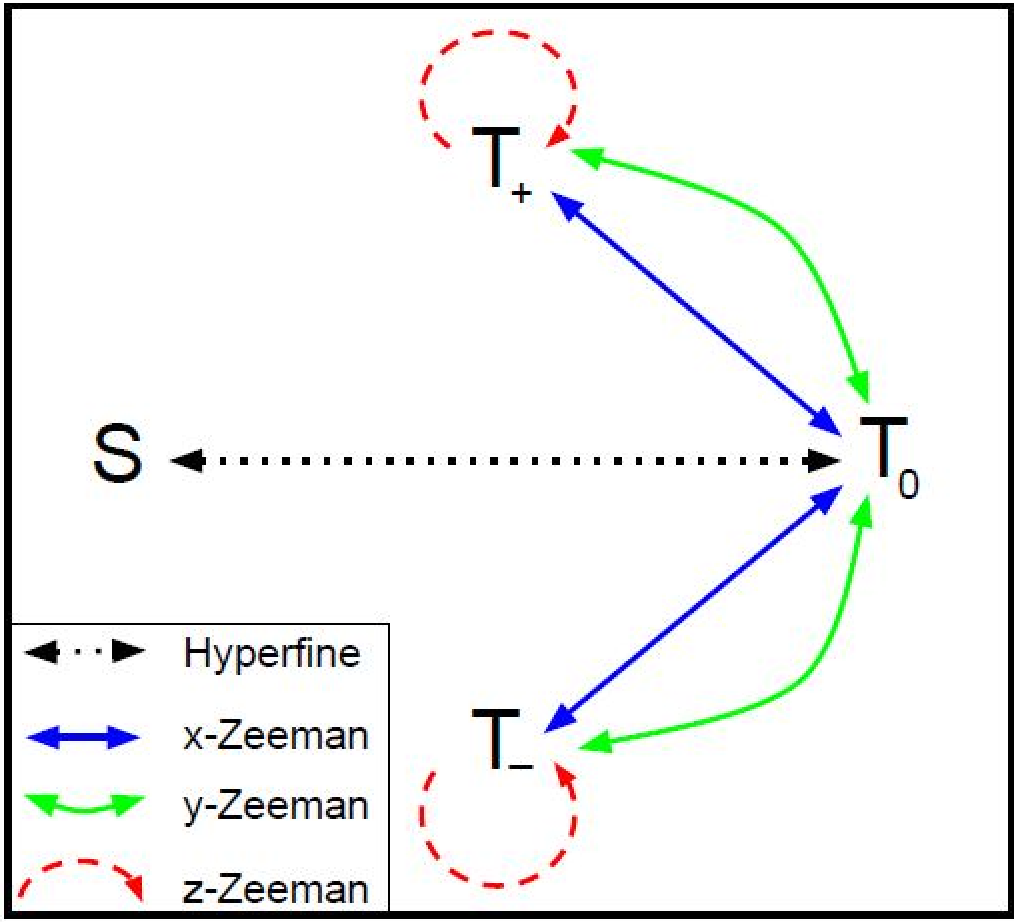
$$H = \gamma \mathbf{B} \cdot (\hat{S}_1 + \hat{S}_2) + \hat{I} \cdot \mathbf{A} \cdot \hat{S}_2$$

Results: State Transitions



Singlet (S) and triplet (T_0, T_+, T_-) yields vs. geomagnetic yield orientation for various hyperfine coupling strengths

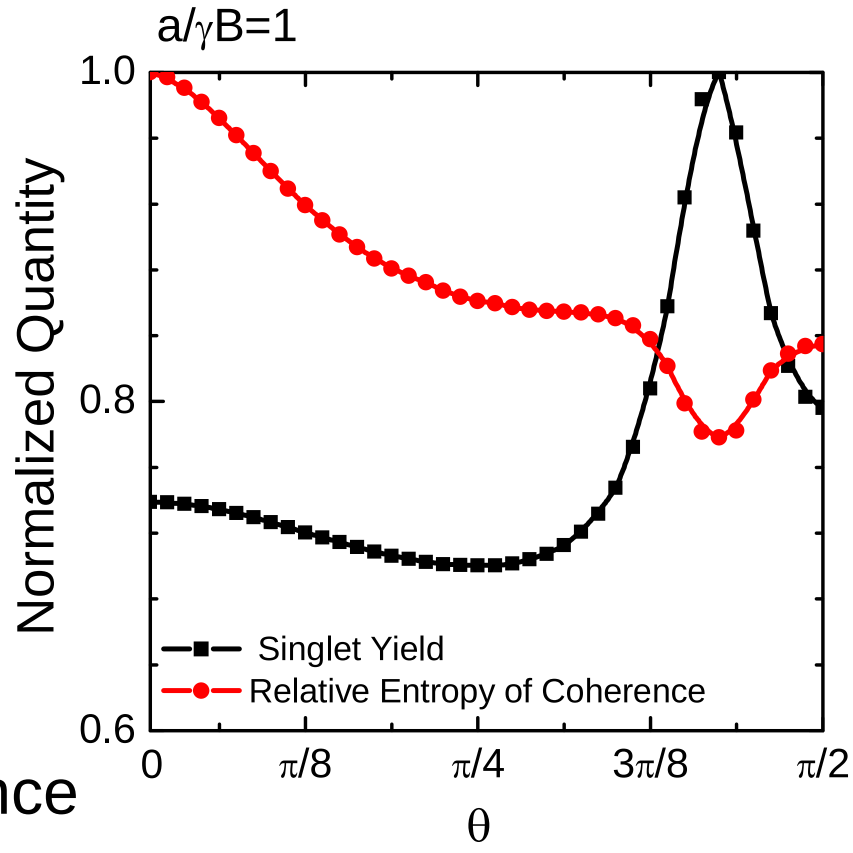
Results: State Transitions



Spin transition for hyperfine and Zeeman Hamiltonian interactions

Decoherence: State Transitions Peaks

- The singlet yield plot has conspicuous peaks at certain magnetic field inclinations



- Coherence quantifier

$$C(\rho) = S(\rho_{diag}) - S(\rho)$$

where, von Neumann entropy: $S(\rho) \equiv -\mathrm{tr}\{\rho \ln \rho\}$

- The peak in singlet yield corresponds to the dip in coherence

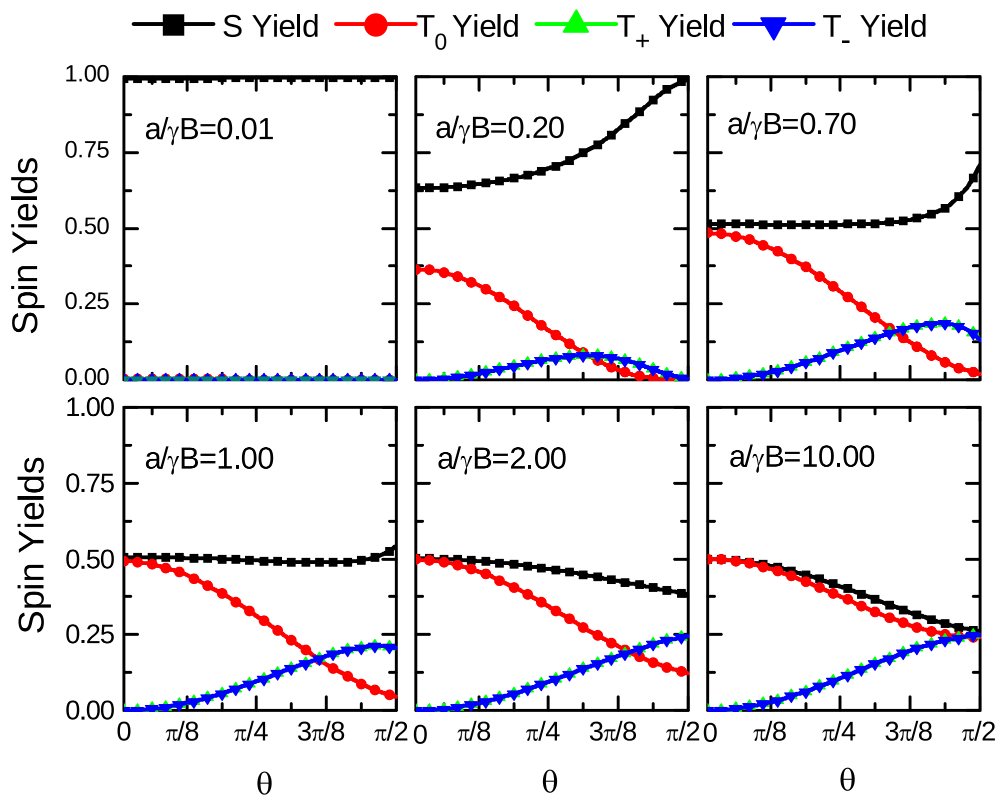
Results: Decoherence

- The coherence time of the radical pair spin state is around tens of microseconds

- Two decoherence mechanisms in the systems
  - Nuclear Decoherence (Intrinsic)
    - When environmental interactions are not taken into account
  - Environmental Decoherence (Extrinsic)
    - Environmental interaction leading to lose of radical pair coherence

Nuclear Decoherence

- The nuclear decoherence does not disrupt the compass action
- The peak disappears when nuclear state is disentangled from radical pair state



Environmental Decoherence

- With Lindblad noise operators the master equation gets modified as:

$$\dot{\rho} = -\frac{i}{\hbar}[H,\rho] + k\sum_{i=1}^{8} P_i\rho P_i^{\dagger} - \frac{1}{2}(P_i^{\dagger}P_i\rho + \rho P_i^{\dagger}P_i) + \sum_i \Gamma_i\left(L_i\rho L_i^{\dagger} - \frac{1}{2}(L_i^{\dagger}L_i\rho + \rho L_i^{\dagger}L_i)\right).$$

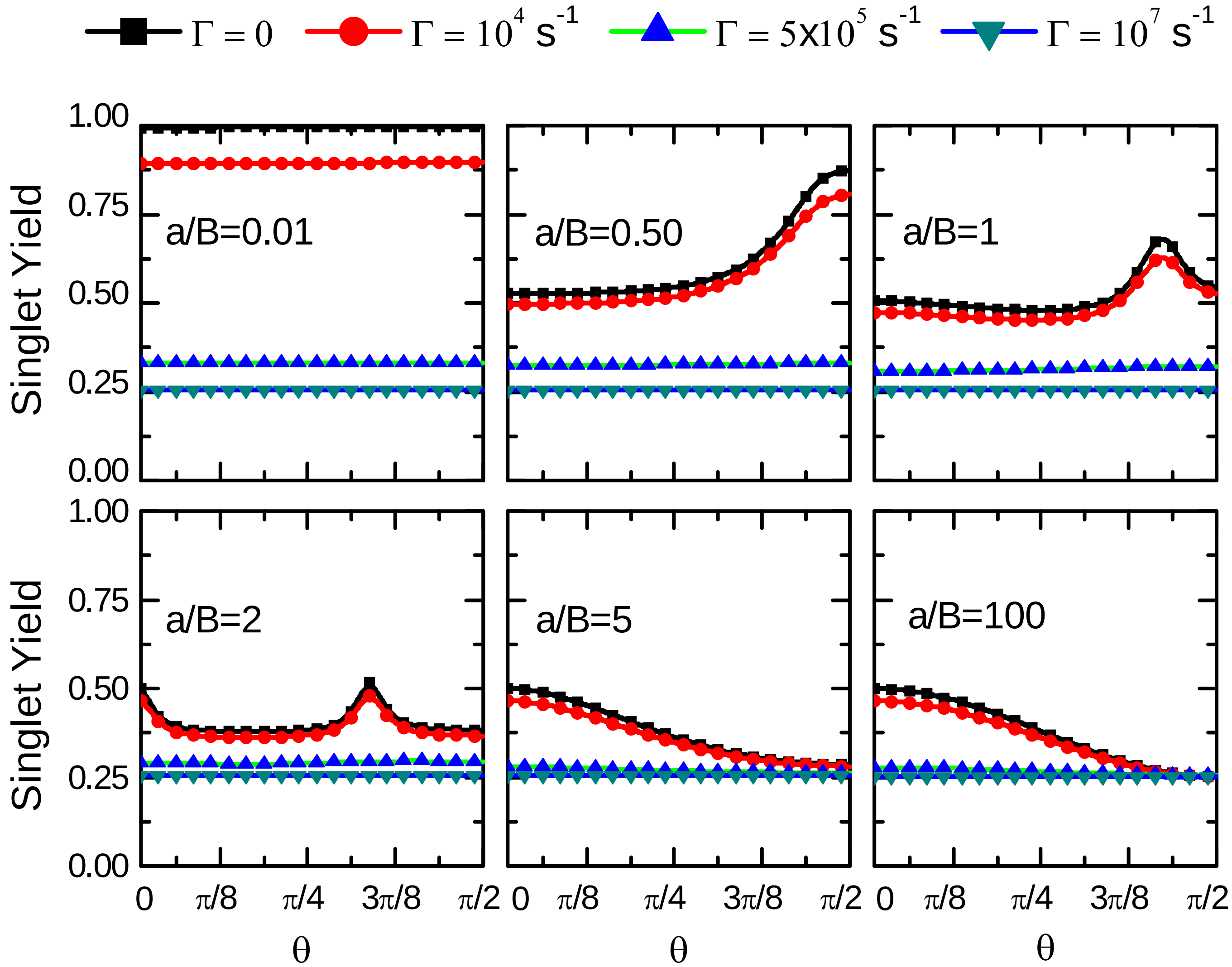
Where, Γ is noise rate.

The Lindblad noise operators L_i are given as:

$$\begin{aligned}
L_1 &= I_2 \otimes \sigma_x \otimes I_2 \\
L_2 &= I_2 \otimes \sigma_y \otimes I_2 \\
L_3 &= I_2 \otimes \sigma_z \otimes I_2 \\
L_4 &= I_2 \otimes I_2 \otimes \sigma_x \\
L_5 &= I_2 \otimes I_2 \otimes \sigma_y \\
L_6 &= I_2 \otimes I_2 \otimes \sigma_z
\end{aligned}$$

E. M. Gauger, et al. PRL 106.4 2011

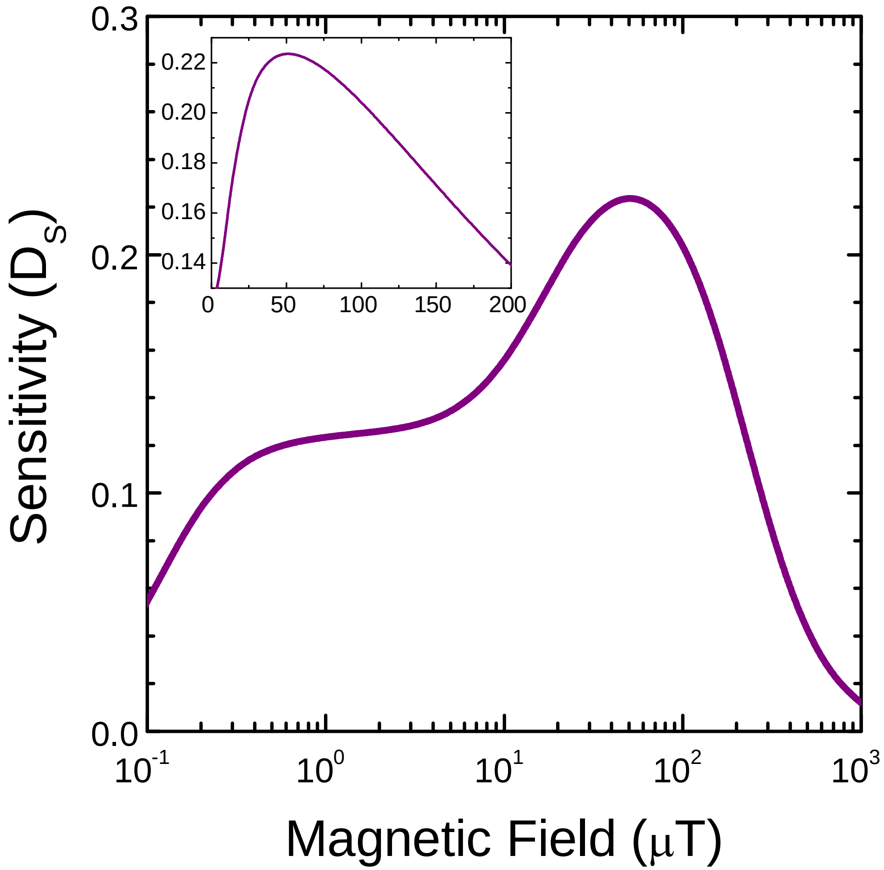
Environmental Decoherence



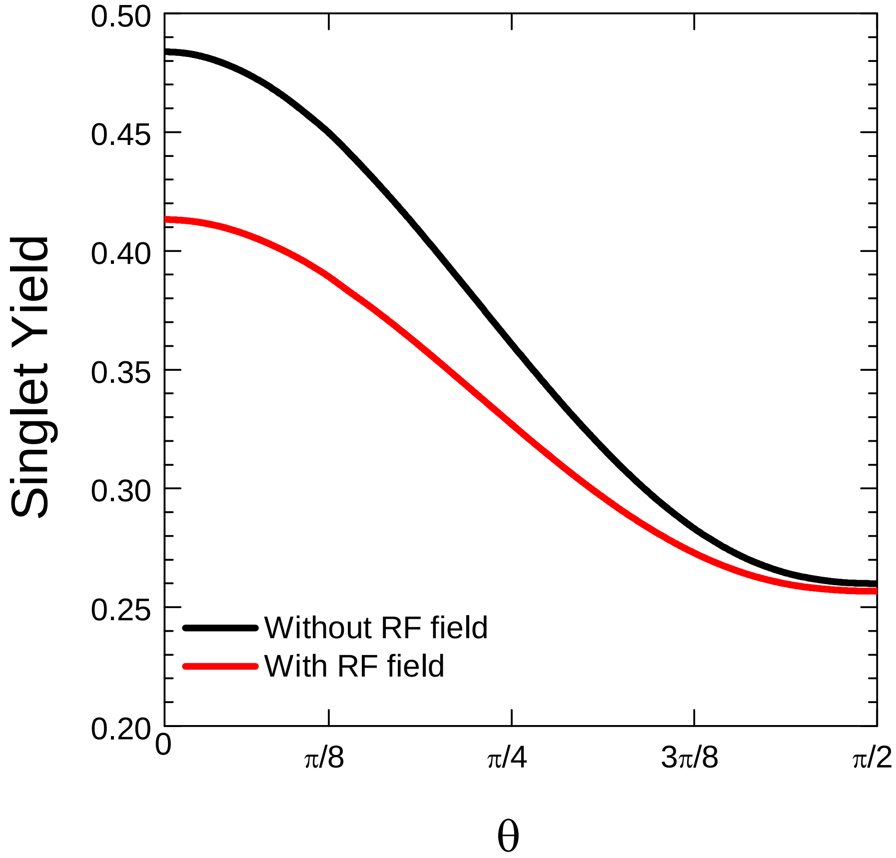
Functional Window

- Functional Window
  - Selectivity of avian compass (±30% around geomagnetic field)
- Vital for navigation
- Analyzed the compass sensitivity as function of the geomagnetic field intensity for a large number of compass parameters
- Observed ‘functional window’ behavior in RP system with ‘biologically feasible parameters set’

Functional Window



Functional Window



RF Disruption (30%)

$(a_x, a_y, a_z, k_s, k_t) = (0.345G, 0.345G, 9G, 2x10^4\ s^{-1}, 2x10^4\ s^{-1})$

C. T. Rodgers, *PNAS, 2009*

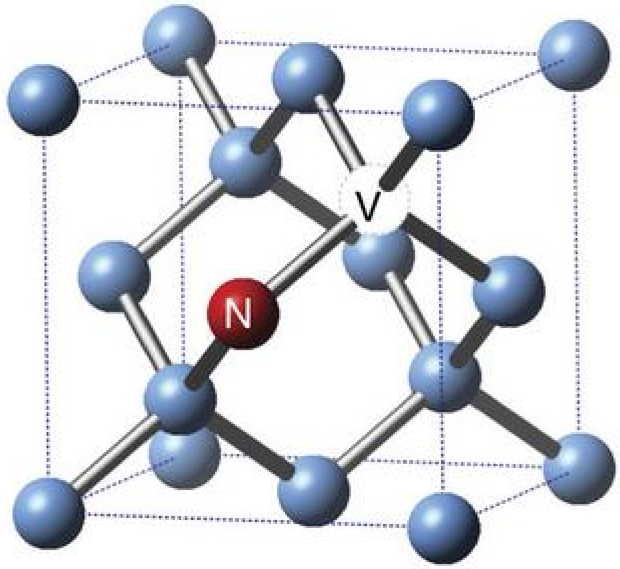
Conclusions & Outlook

- Coherence is believed to be persisting upto microseconds
- In our study, we have incorporated all behavioral characteristics of the compass
- Collaborative role of Zeeman and hyperfine interaction is highlighted
- Spin transitions giving rise to magneto-sensitive behavior of avian compass are identified
- Distinctive role of nuclear and environmental decoherence is identified

Conclusions and Outlook

- Biologically feasible parameter regime is discovered for avian compass
- Envisaging solid state emulation of the avian compass ➔ terrestrial magnetism based positioning
- Diamond NV center spin system seems to be a potential candidate

G. Balasubramanian, et al., Nat. Mater. 2009.



$$H = DS_Z^2 + E(S_x^2 - S_y^2) + g\mu_B \mathbf{B}\cdot\hat{S} - \hat{S}\cdot\mathbf{A}\cdot\hat{I}$$

See poster by Vishvendra Singh Poonia

THANK YOU!