Quantum effects in avian magnetoreception

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2013-03-02

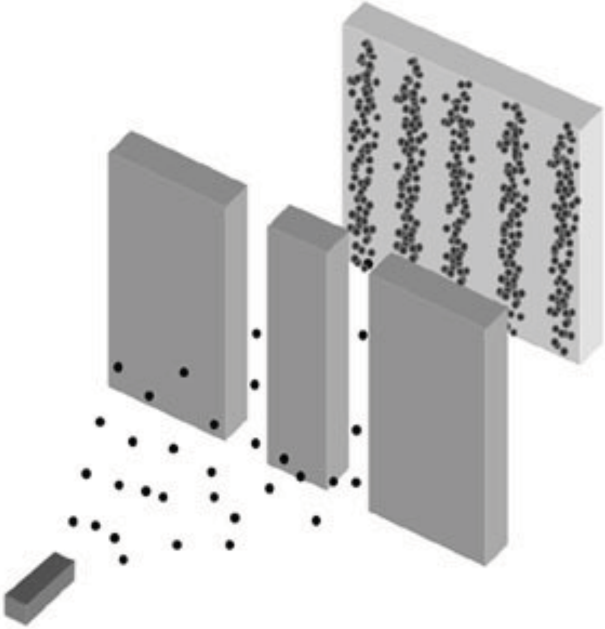
Alexander von Humboldt
Stiftung/Foundation

DFG Deutsche Forschungsgemeinschaft

MARIE CURIE ACTIONS

Quantum Effect: Basic concepts

- Quantum coherence



Quantum superposition

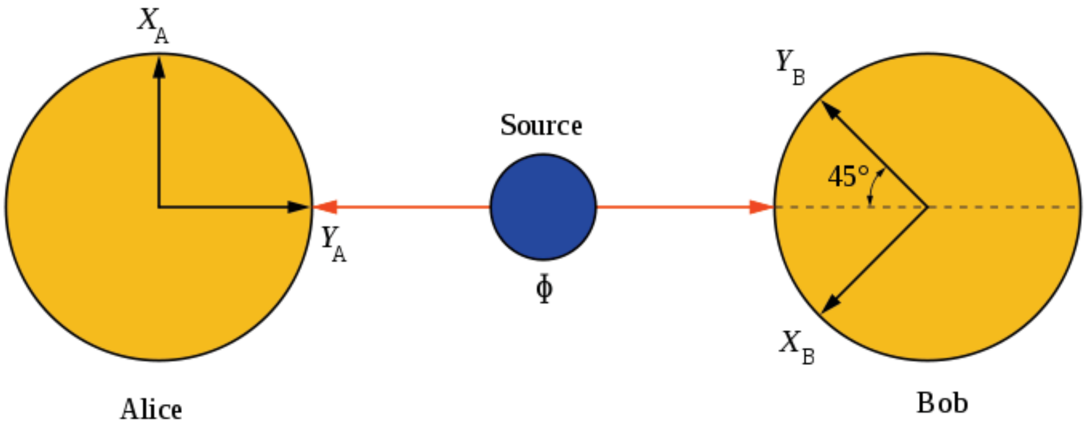
$$|\cdot\rangle = |L\rangle + |R\rangle$$

Wave interference

Quantum Effect: Basic Concepts

- Quantum entanglement

Sabre’s talk



- ✓ Quantum teleportation
- ✓ Quantum key distribution
- ✓ Quantum computation

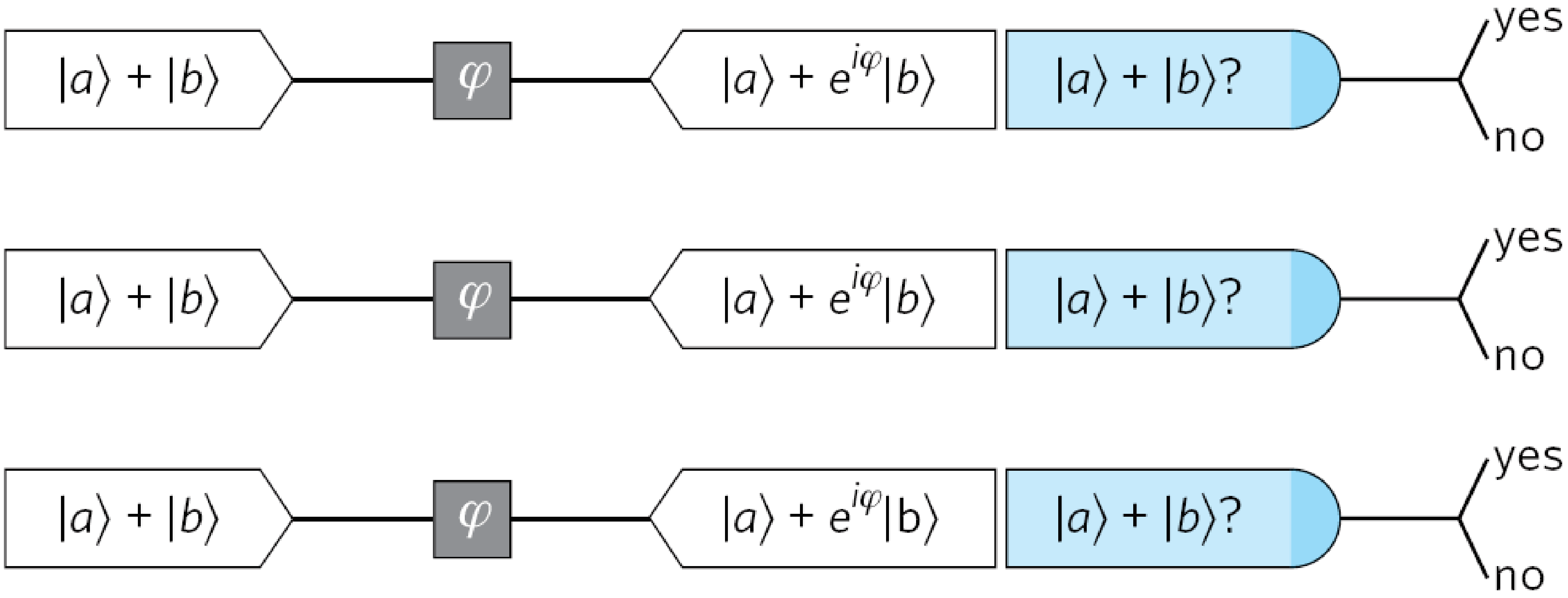
Quantum superposition with two or more particles

$$\frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle\right)$$

$$\mathbf{C}[A(a),B(b)] + \mathbf{C}[A(a),B(b')] + \mathbf{C}[A(a'),B(b)] - \mathbf{C}[A(a'),B(b')] \le 2, \quad \boxed{2\sqrt{2}}$$

Quantum Effect: Basic Concepts

Mankei's talk



Frequency measurement

***N* independent "particles"**

$$(\text{signal}) = \langle\sigma_z\rangle = -\cos\omega T$$

$$(\text{noise}) = \Delta\sigma_z = \sqrt{1-\cos^2\omega T} = |\sin\omega T|$$

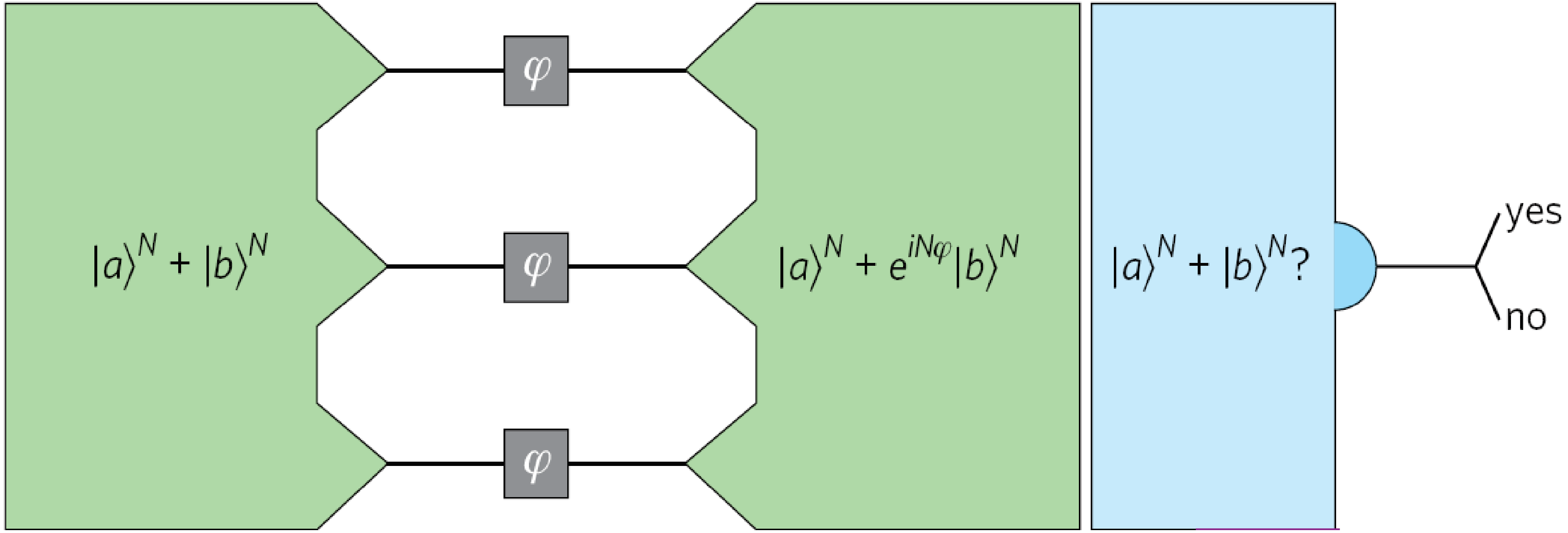
$$\Delta(\omega T) = \boxed{\frac{1}{\sqrt{N}}}\,\frac{(\text{noise})}{|d(\text{signal})/d(\omega T)|} = \frac{1}{\sqrt{N}}$$

standard quantum limit
(shot noise limit)

Quantum Effect: Basic Concepts

Mankei's talk

- Quantum entanglement



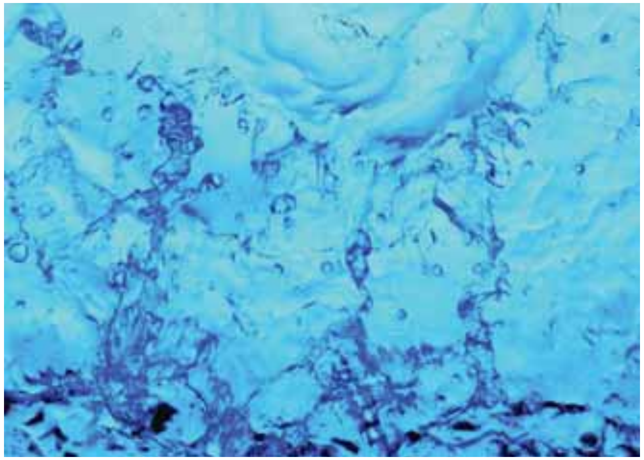
$$\Delta(\omega T) = \boxed{\frac{1}{\sqrt{\nu}}} \frac{(\text{noise})}{|d(\text{signal})/d(\omega T)|} = \frac{1}{\sqrt{\nu}} \boxed{\frac{1}{N}}$$

Heisenberg limit

$\nu =$ (number of trials)

***N* cat-state atoms**

Hot and Macroscopic Quantum Effect?



- Thermal energy overwhelms signatures of energy quantization

$$k_B T >> \hbar\omega$$

- Quantum decoherence

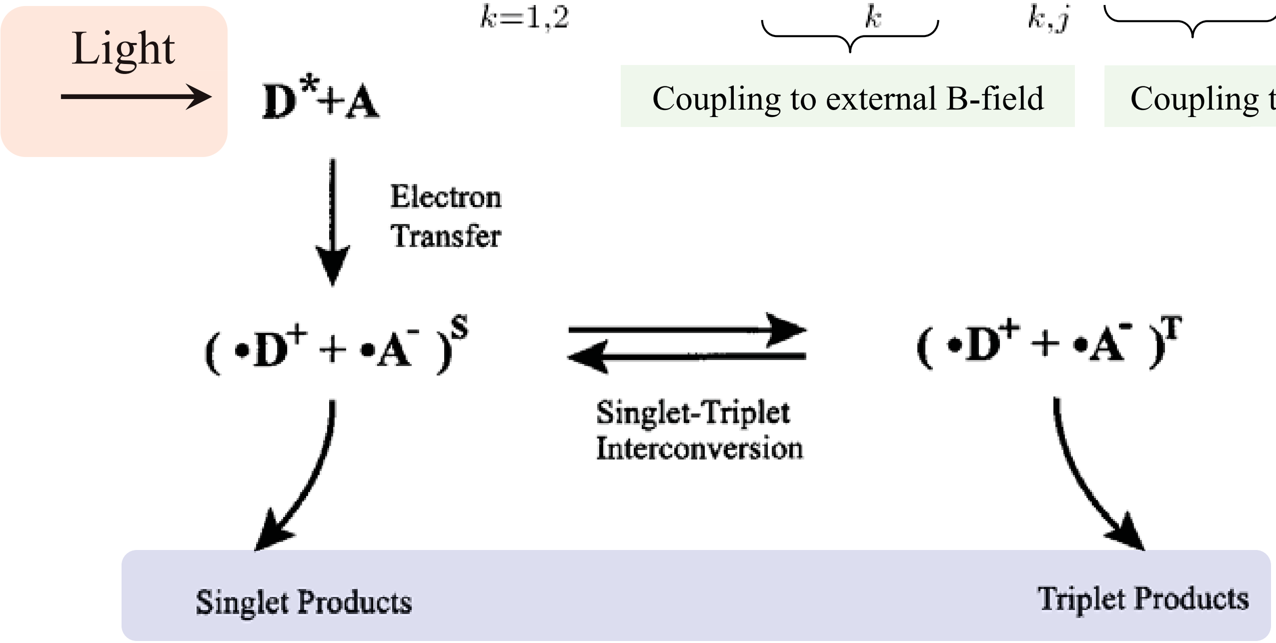
$$|\psi_1\rangle + e^{\phi}|\psi_2\rangle \rightarrow |\psi_1\rangle\langle\psi_1| + |\psi_2\rangle\langle\psi_2|$$

Chemical compass model for avian magnetoreception

Avian Magnetoreception: Radical pair mechanism

$h\nu \longrightarrow \begin{matrix} D^{+} - A^{-} \\ \uparrow \cdots\cdot \downarrow \end{matrix} \longrightarrow$ Charge recombination → Nerve signal

$$H = \sum_{k=1,2} H_k = -\gamma_e \vec{B} \cdot \underbrace{\sum_{k} \vec{S}_k}_{\text{Coupling to external B-field}} + \sum_{k,j} \underbrace{\vec{S}_k \cdot \hat{\lambda}_{k_j} \cdot \vec{I}_{k_j}}_{\text{Coupling to local nuclear-spin envionment}}$$



Light

$D^{*} + A$

Electron Transfer

$(\bullet D^{+} + \bullet A^{-})^{S}$

Singlet-Triplet Interconversion

$(\bullet D^{+} + \bullet A^{-})^{T}$

Singlet Products

Triplet Products

$$\left|T_0\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle + \left|\downarrow\uparrow\right\rangle\right)$$

$$\left|T_+\right\rangle = \left|\uparrow\uparrow\right\rangle$$

$$\left|T_-\right\rangle = \left|\downarrow\downarrow\right\rangle$$

$$\left|S\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$

$$\frac{d\rho_s}{dt} = -i[H_0, \rho_s] - \frac{k_S}{2} \sum_{i} \left(Q_S \rho_s + \rho_s Q_S\right) - \frac{k_T}{2} \left(Q_T \rho_s + \rho_s Q_T\right) + \mathcal{L}(\rho)$$

$$\mathcal{L}(\rho) = \sum_{k} \xi_k \left[\mathcal{L}_k \rho \mathcal{L}_k^{\dagger} - \frac{1}{2}\left(\mathcal{L}_k^{\dagger}\mathcal{L}_k \rho - \rho \mathcal{L}_k^{\dagger}\mathcal{L}_k\right)\right].$$

Coherent dynamics and design principles for a chemical compass

- How do quantum feature/entanglement exist in a chemical compass?

- How to verify quantum effect in a chemical compass?

  - *Estimate quantum correlation/entanglement of radical pair spin states*

- How to design an artificial chemical compass?

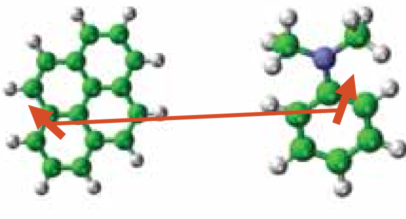
  - *Design a bio-mimetic weak magnetic field sensor*

  - *Understand quantum features responsible for its magnetic sensitivity*

Quantum Effect in Avian Magnetoreception

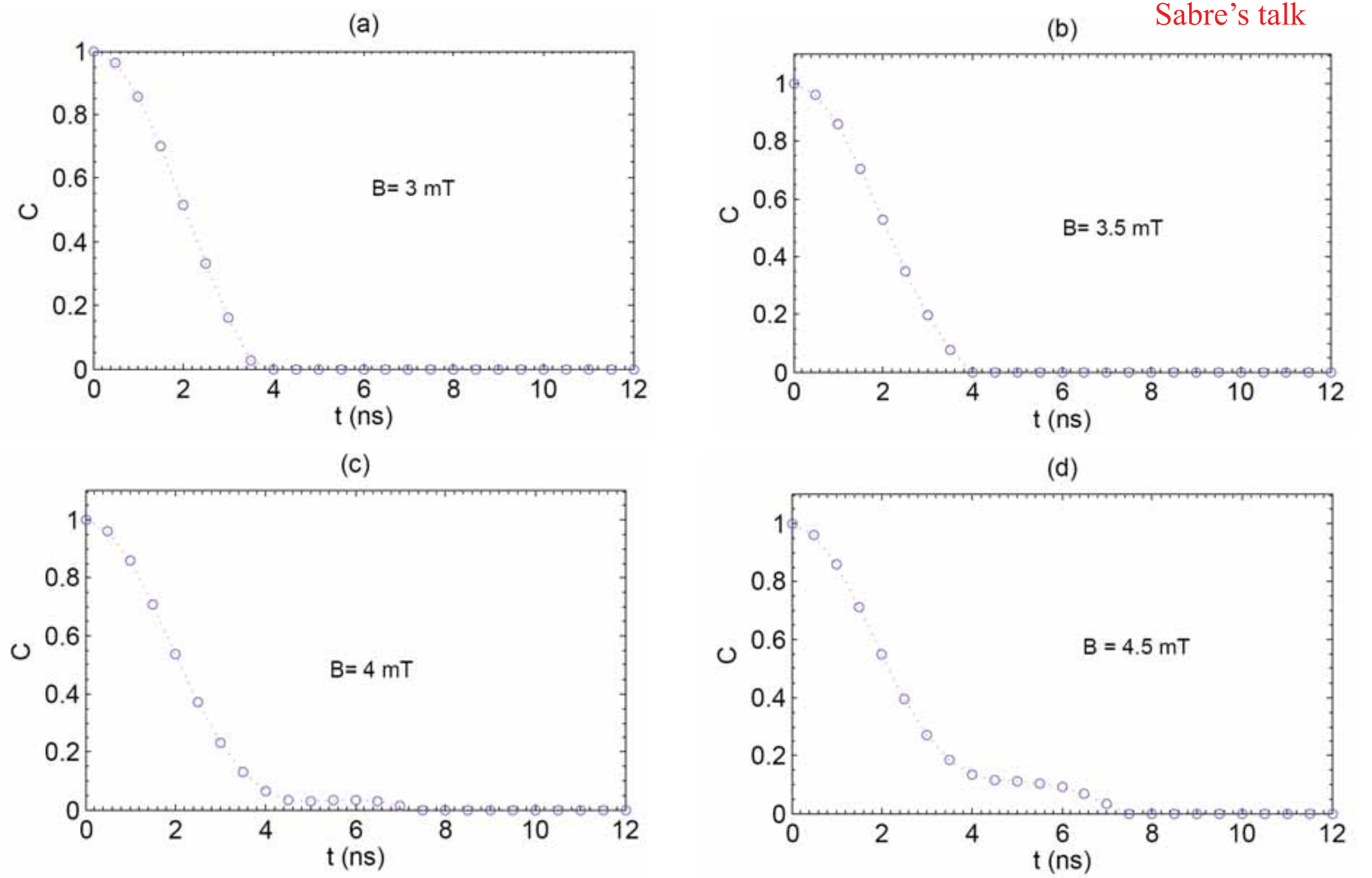
- How does quantum coherence/entanglement exist in RPM?
- Is quantum coherence/entanglement relevant to the functioning of a chemical compass?

Quantum Entanglement in a Chemical Compass

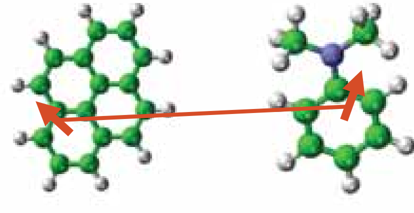


Jianming Cai, G. G. Guerreschi, H. Briegel, Phys. Rev. Lett 104, 220502 (2010)

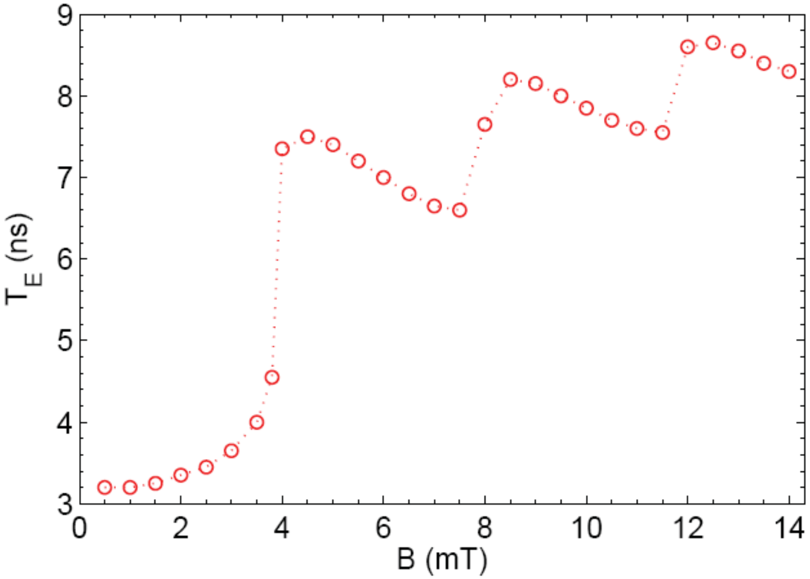
Sabre’s talk



Quantum Entanglement in a Chemical Compass



- Entanglement lifetime

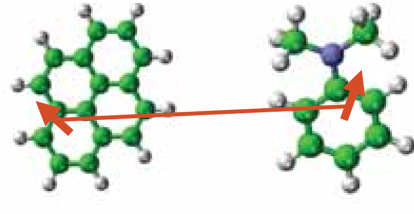


Jyrki's lectures

Discontinuity in the lifetime T_E of entanglement as a function of B

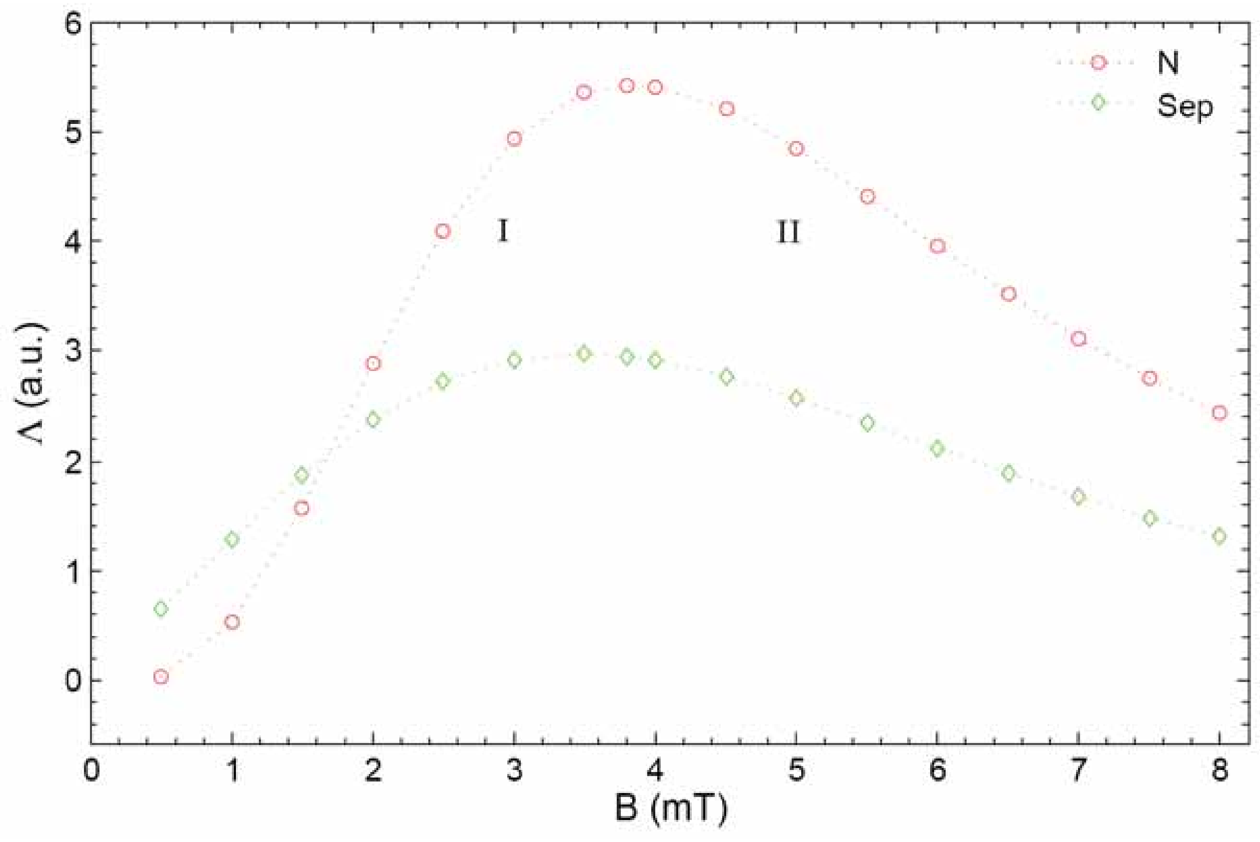
- *Non-Markovian effect from the finite size nuclear spin environment*

Entanglement enhances magnetic field sensitivity?



5000 separable states vs. entangled states

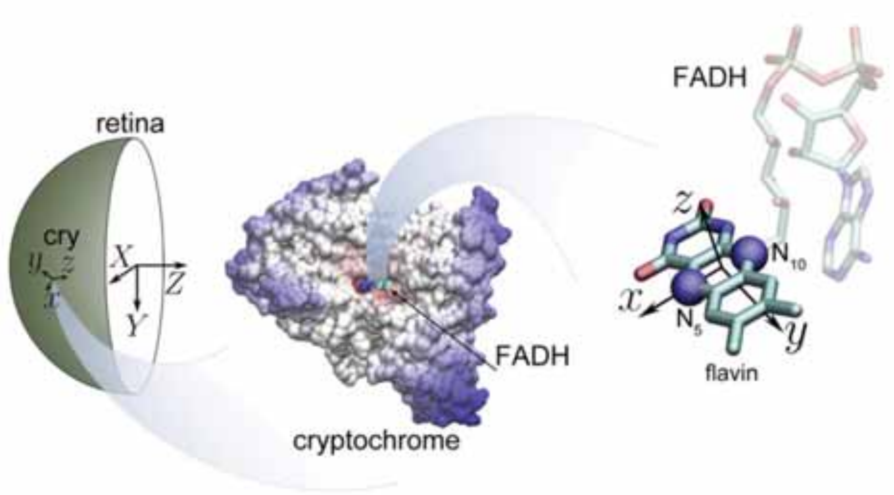
$$|S\rangle = \frac{1}{\sqrt{2}}(|\downarrow\uparrow\rangle - |\uparrow\downarrow\rangle)$$

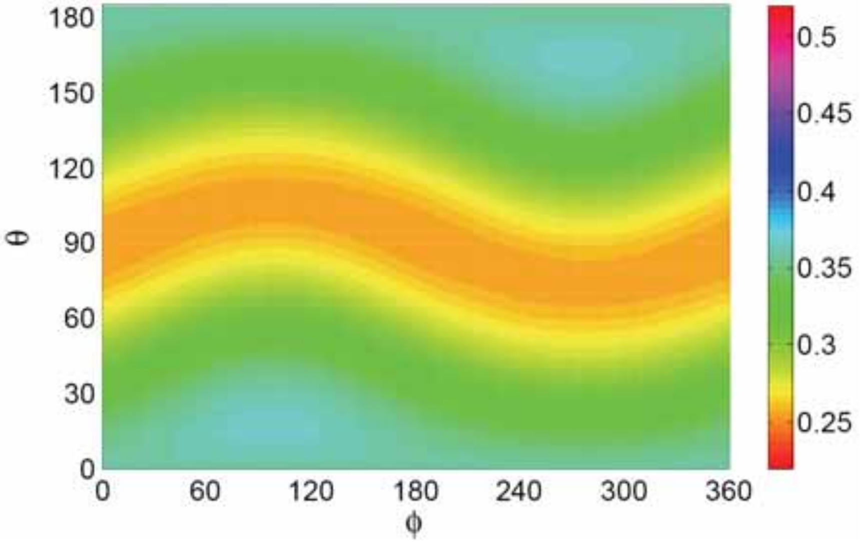


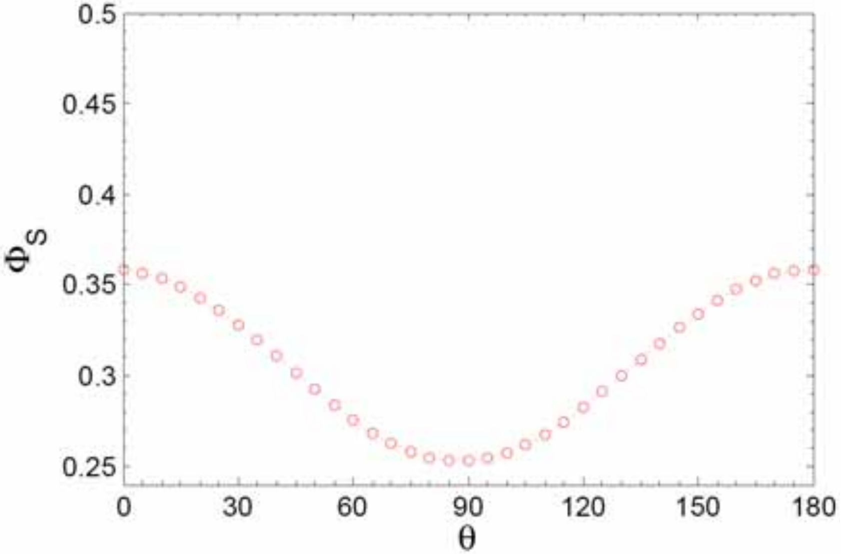
Entanglement is necessary for high magnetic-field sensitivity

Magnetic Directional Sensitivity of a Chemical Compass

$$\vec{B} = B(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$







K. Schulten (UIUC) 2010

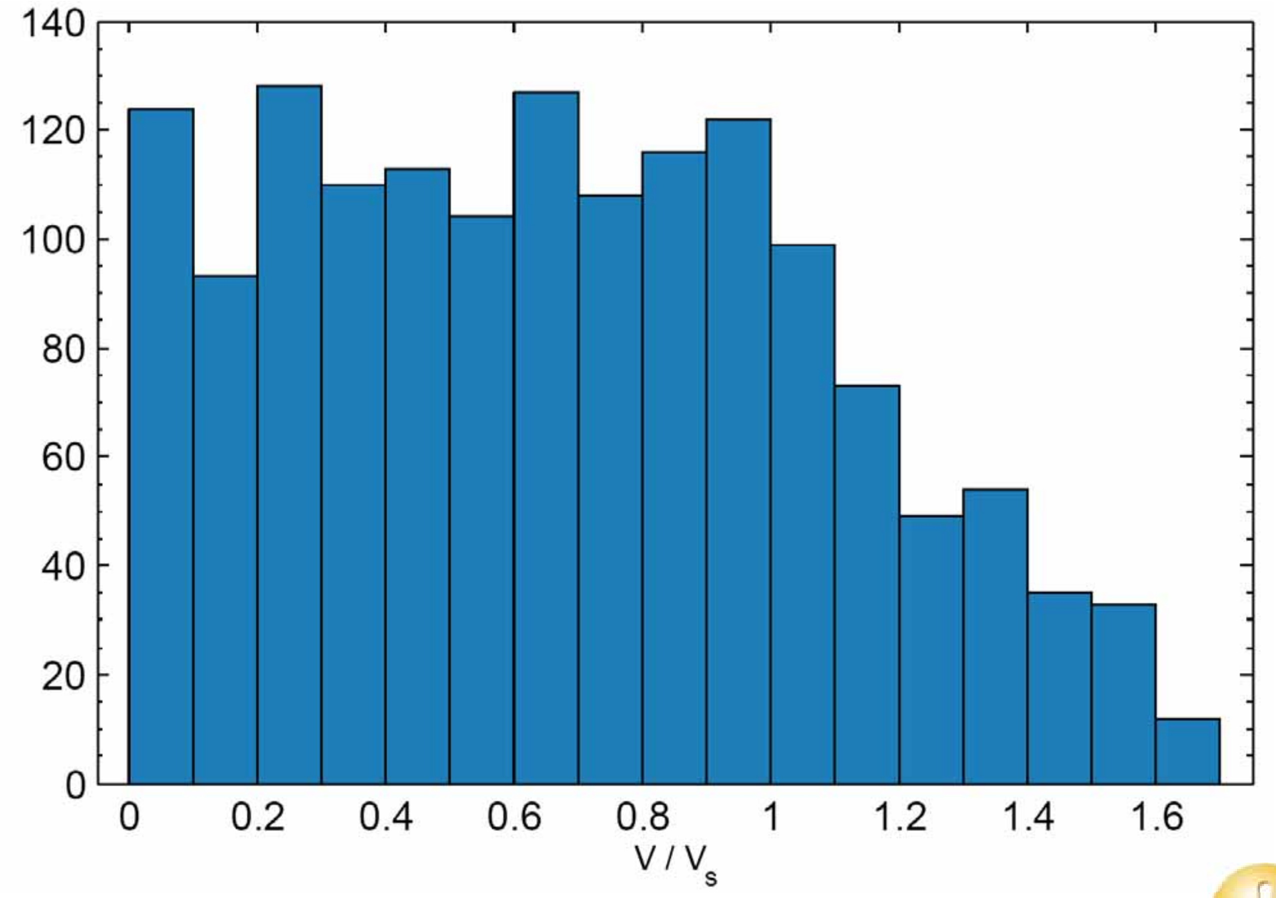
- Radical pair lifetime

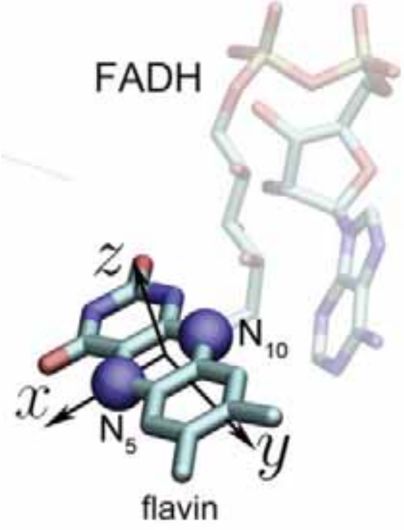
$$\tau = k^{-1} = 2\mu s$$

Magnetic Directional Sensitivity of a Chemical Compass

1500 product states vs. entangled states

$$V = \frac{\max \Phi_s - \min \Phi_s}{\max \Phi_s + \min \Phi_s}$$





- Many separable states can give a high angular dependence
- Here entanglement seems not to play a significant role

Model matters!

Quantum Coherence and Entanglement in a Chemical Compass

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

Sustained Quantum Coherence and Entanglement in the Avian Compass

Erik M. Gauger,[1] Elisabeth Rieper,[2] John J. L. Morton,[1,3] Simon C. Benjamin,[2,1,*] and Vlatko Vedral[2,3,4]
[1]*Department of Materials, University of Oxford, Parks Road, Oxford OX1 3PH, United Kingdom*
[2]*Centre for Quantum Technologies, National University of Singapore, Singapore*
[3]*Clarendon Laboratory, University of Oxford, Parks Road, OX1 3PU, United Kingdom*
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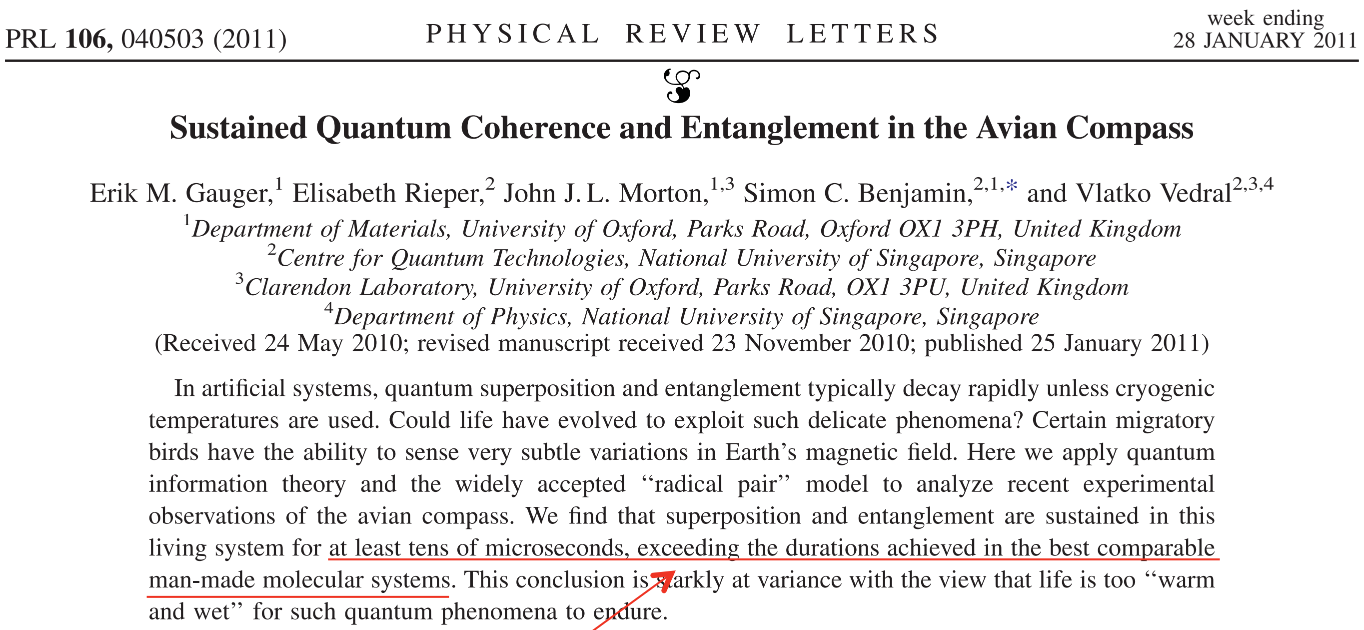
(Received 24 May 2010; revised manuscript received 23 November 2010; published 25 January 2011)

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.

The results are shown in Fig. 2. We conclude that if the oscillating field is to disorient the bird, as experiments showed, then the decay rate k should be approximately $10^4\ \mathrm{s}^{-1}$ or less. For higher values of k (shorter time scales

sensitivity fails. This is shown in Fig. 3. Conservatively, we can say that when $\Gamma \geq k$, the angular sensitivity is highly degraded. This is remarkable, since it implies the decoherence time of the two-electron compass system is of order 100 μs or more [30]. For context we note that the best laboratory experiment involving preservation of a molecular electron spin state has accomplished a decoherence time of 80 μs [31].

Quantum Coherence and Entanglement in a Chemical Compass



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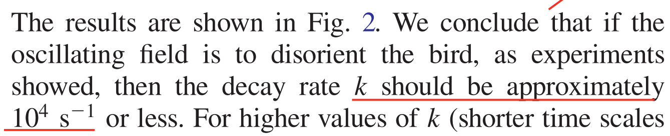

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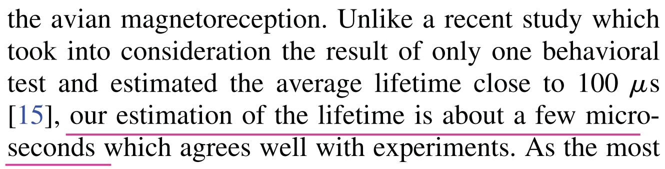
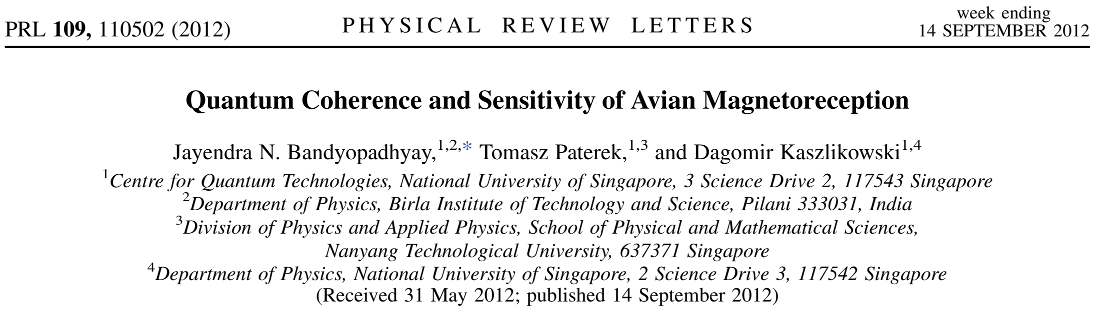


the avian magnetoreception. Unlike a recent study which took into consideration the result of only one behavioral test and estimated the average lifetime close to 100 μs [15], our estimation of the lifetime is about a few microseconds which agrees well with experiments. As the most



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

Quantum Coherence and Sensitivity of Avian Magnetoreception

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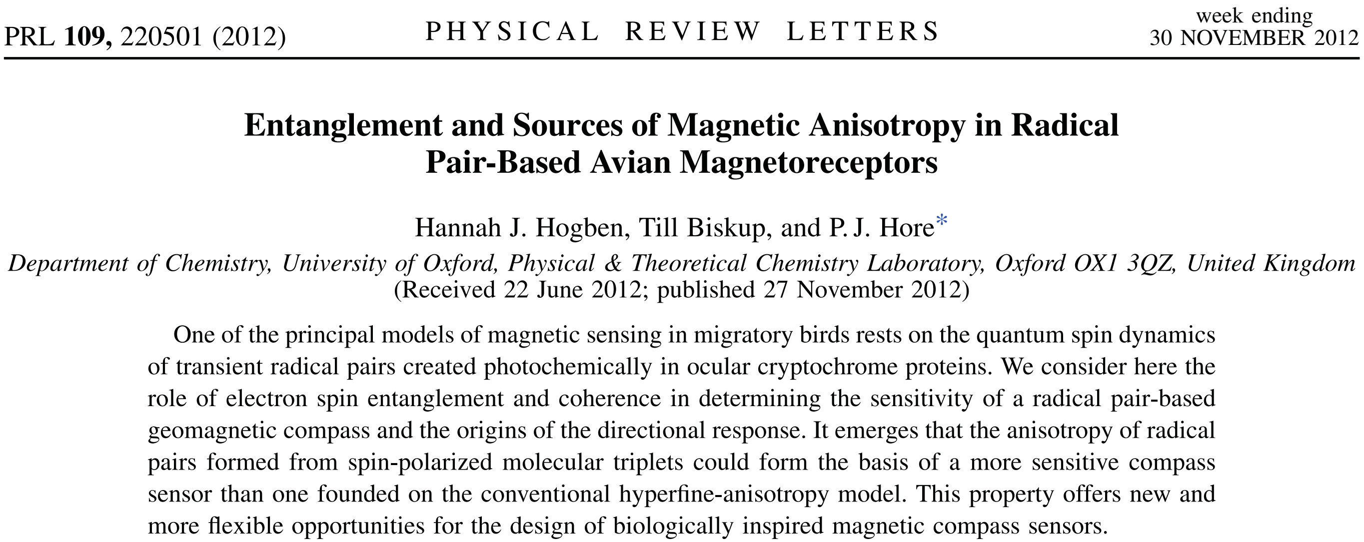
(Received 31 May 2012; published 14 September 2012)

Quantum Coherence and Entanglement in a Chemical Compass



PRL **109,** 220501 (2012) PHYSICAL REVIEW LETTERS week ending 30 NOVEMBER 2012

Entanglement and Sources of Magnetic Anisotropy in Radical Pair-Based Avian Magnetoreceptors

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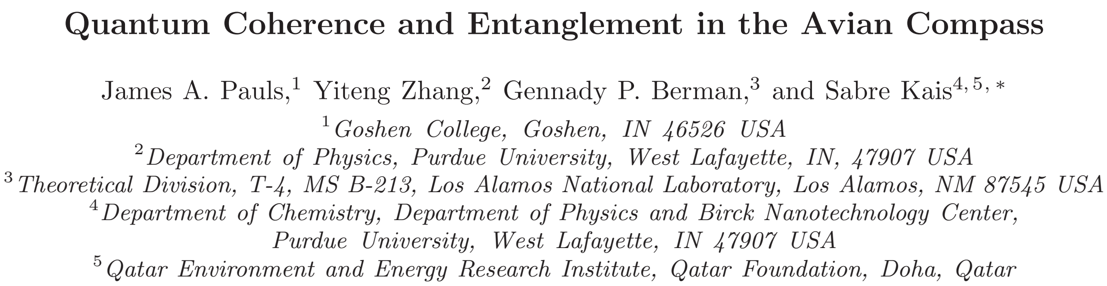
(Received 22 June 2012; published 27 November 2012)

One of the principal models of magnetic sensing in migratory birds rests on the quantum spin dynamics of transient radical pairs created photochemically in ocular cryptochrome proteins. We consider here the role of electron spin entanglement and coherence in determining the sensitivity of a radical pair-based geomagnetic compass and the origins of the directional response. It emerges that the anisotropy of radical pairs formed from spin-polarized molecular triplets could form the basis of a more sensitive compass sensor than one founded on the conventional hyperfine-anisotropy model. This property offers new and more flexible opportunities for the design of biologically inspired magnetic compass sensors.



Quantum Coherence and Entanglement in the Avian Compass

James A. Pauls,[1] Yiteng Zhang,[2] Gennady P. Berman,[3] and Sabre Kais[4, 5, *]

[1] *Goshen College, Goshen, IN 46526 USA*
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Model matters!

It is unclear whether quantum coherence/entanglement is essential for avian magnetoreception?

Entanglement detection in radical pair reactions

- ❖ Entanglement may give us new information about the radical pair dynamics.

- How to estimate quantum correlation of radical pair states

  from the measurement of chemical product?

Model chemical compass with optimal sensitivity

- ❖ Reference-and-Probe model

One radical pair is free of hyperfine couplings

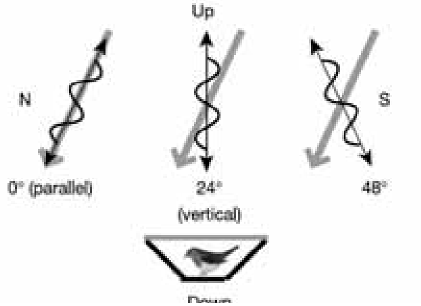
Biophysical Journal Volume 96 April 2009 3451–3457 3451

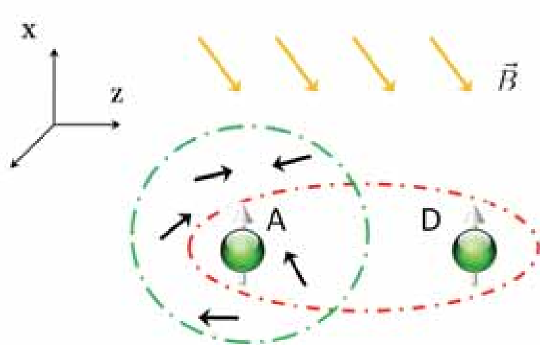
Magnetic Compass of Birds Is Based on a Molecule with Optimal Directional Sensitivity

Thorsten Ritz,[†*] Roswitha Wiltschko,[‡*] P. J. Hore,[§*] Christopher T. Rodgers,[§] Katrin Stapput,[‡] Peter Thalau,[‡] Christiane R. Timmel,[§] and Wolfgang Wiltschko[‡]

[†]Department of Physics and Astronomy, University of California, Irvine, California; [‡]Fachbereich Biowissenschaften der J.W.Goethe-Universität, Frankfurt am Main, Germany; and [§]Department of Chemistry, University of Oxford, Oxford, United Kingdom

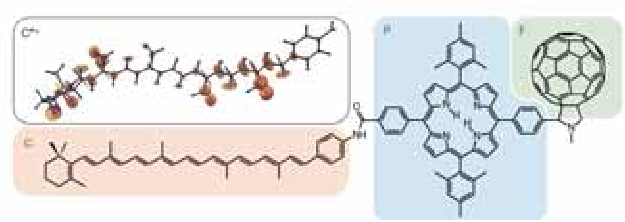
Resonant experiments with European robin

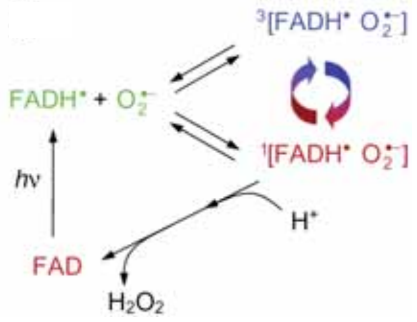




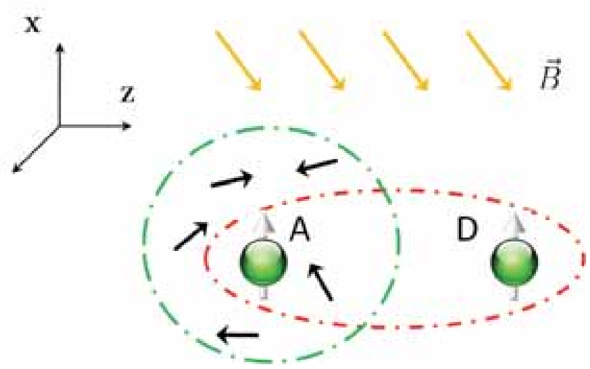
Carotenoid-**P**orphyrin- **F**ullerene

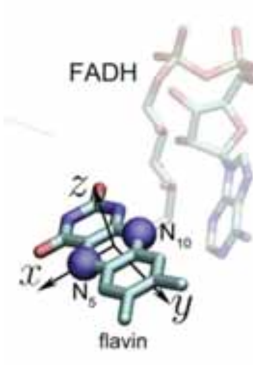
Peter Hore… (Oxford)

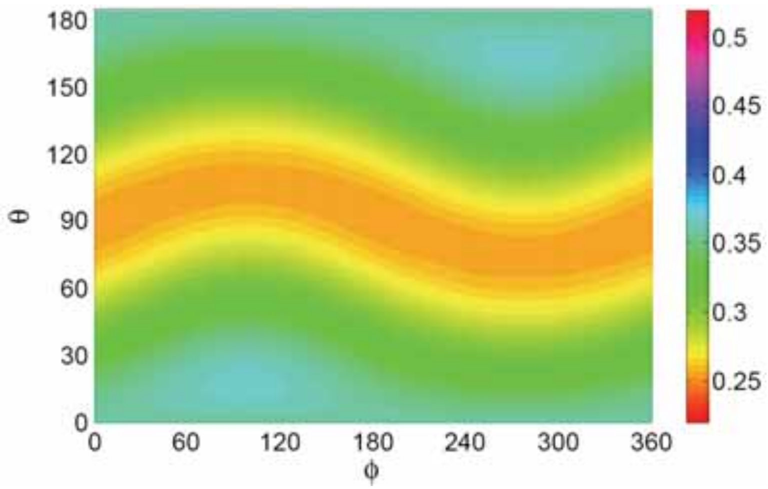




Entanglement detection in radical pair reactions

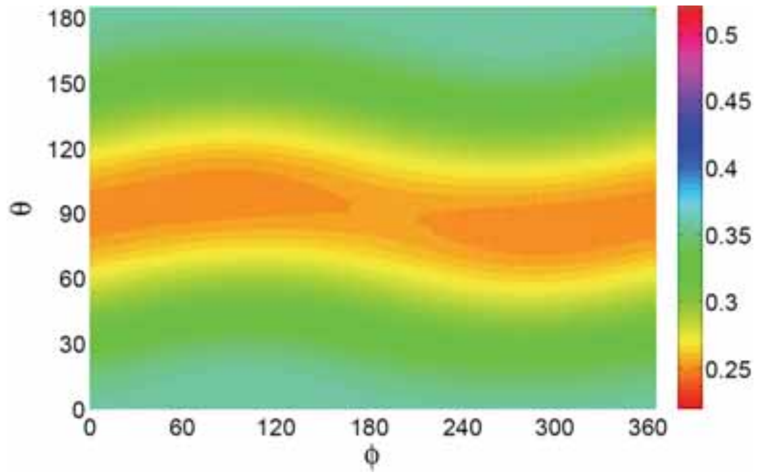






$$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

Nucleus	a_{iso}	λ_i	Principal hyperfine axes		
N	0.393	-0.498	0.4380	0.8655	-0.2432
		-0.492	0.8981	-0.4097	0.1595
		0.989	-0.0384	0.2883	0.9568
N	0.212	-0.242	0.9703	-0.2207	0.0992
		-0.234	0.2383	0.9426	-0.2340
		0.476	-0.0419	0.2506	0.9672
H	0.390	-0.062	-0.1902	0.3965	0.8981
		-0.033	0.9156	0.4017	0.0165
		0.095	-0.3542	0.8255	-0.4395
H	-0.158	-0.060	-0.0362	0.2937	0.9552
		-0.044	0.7948	0.5879	-0.1507
		0.104	-0.6059	0.7537	-0.2546
H	-0.769	-0.616	0.9819	0.1883	-0.0203
		-0.168	-0.0348	0.2850	0.9579
		0.784	-0.1861	0.9398	-0.2864



$$(|\uparrow\downarrow\rangle\langle\uparrow\downarrow| + |\downarrow\uparrow\rangle\langle\downarrow\uparrow|)/2$$

- If the radical pair lifetime >> decoherence time, the hyperfine-mediated MFE does not strongly depend on the initial radical pair state

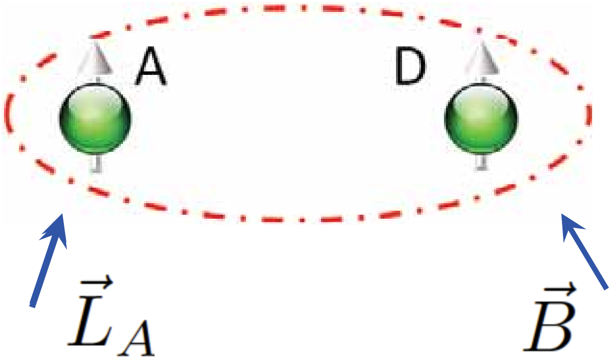
JMC, G. G. Guerreschi, H. J. Briegel, PRL (2010)

Entanglement detection in radical pair reactions

Large gradient field on one radical dominates over the hyperfine couplings and the magnetic field :

$$H \simeq -\gamma_e(\vec{L}_A \cdot \vec{S}_A + \vec{B} \cdot \vec{S}_D)$$

- The singlet product



$$\Phi_S(\vec{L}_A, \vec{B}) = \frac{1}{4} - \frac{1}{4}\langle \hat{A} \otimes \hat{V} \rangle$$

$$\vec{L}_A : \hat{z} \to \hat{A} = \hat{Z}$$

$$\begin{aligned} \vec{B} : \hat{x} &\longrightarrow c\hat{Z} - s\hat{Y} \\ \hat{y} &\longrightarrow c\hat{Z} + s\hat{X} \\ \hat{z} &\longrightarrow \hat{Z} \end{aligned}$$

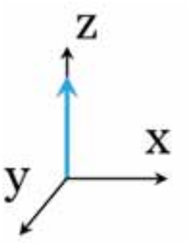
Audenaert & Plenio, NJP (2006)

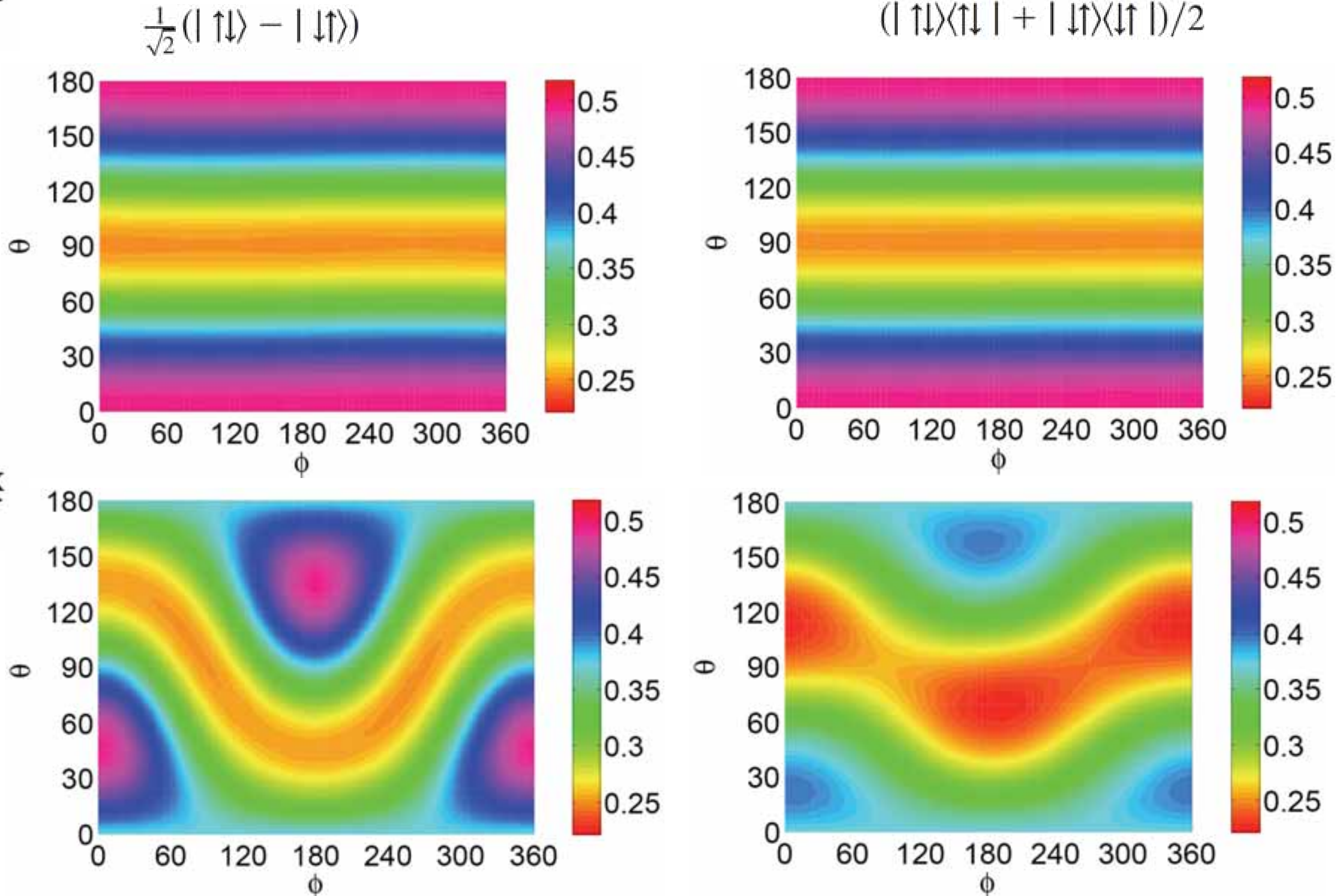
- The gradient field is strong at the location of one spin, and approximately zero at the other.
- Such a field can be created in the vicinity of a hard ferromagnetic nanostructure

Jianming Cai, PRL 106, 100501 (2011), arXiv:1011.5495

Entanglement detection in radical pair reactions

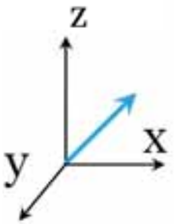
$$\left\langle \hat{Z}\otimes\hat{X}\right\rangle,\left\langle \hat{Z}\otimes\hat{Y}\right\rangle,\left\langle \hat{Z}\otimes\hat{Z}\right\rangle$$



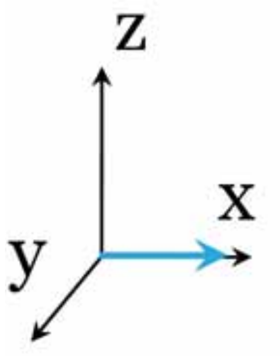


$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$

$(|\uparrow\downarrow\rangle\langle\uparrow\downarrow| + |\downarrow\uparrow\rangle\langle\downarrow\uparrow|)/2$



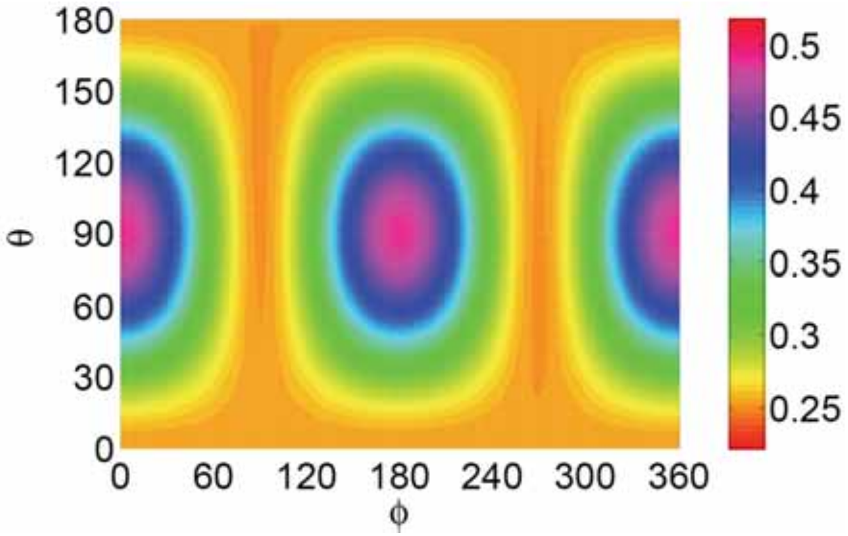
Entanglement detection in radical pair reactions

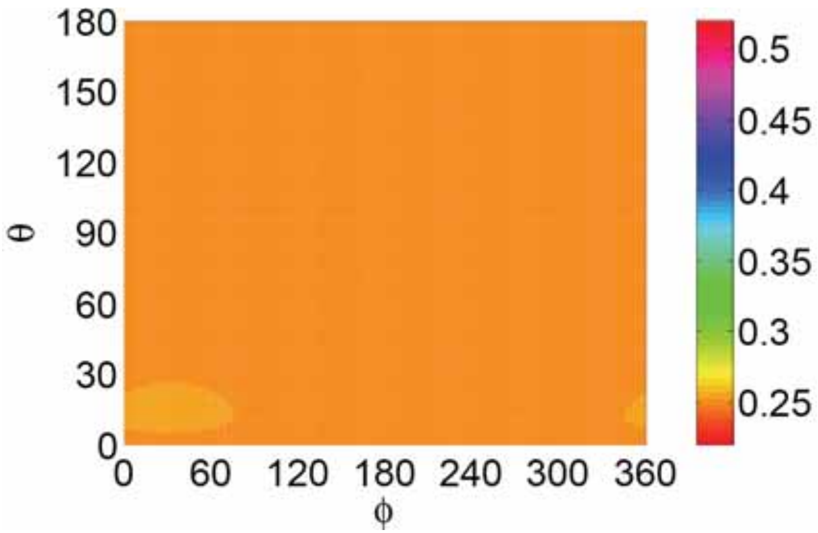


$$\langle \hat{X}\otimes\hat{X}\rangle, \langle \hat{X}\otimes\hat{Y}\rangle, \langle \hat{X}\otimes\hat{Z}\rangle$$

$$\frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle) \longleftrightarrow \frac{1}{\sqrt{2}}(|\rightarrow\leftarrow\rangle - |\leftarrow\rightarrow\rangle)$$

$$(|\uparrow\downarrow\rangle\langle\uparrow\downarrow| + |\downarrow\uparrow\rangle\langle\downarrow\uparrow|)/2$$

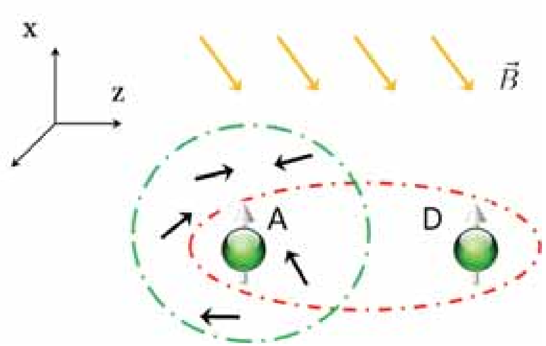




Design principles for a chemical compass

- How to build a chemical compass to detect weak magnetic field?

  - *Understand quantum features responsible for its magnetic sensitivity*

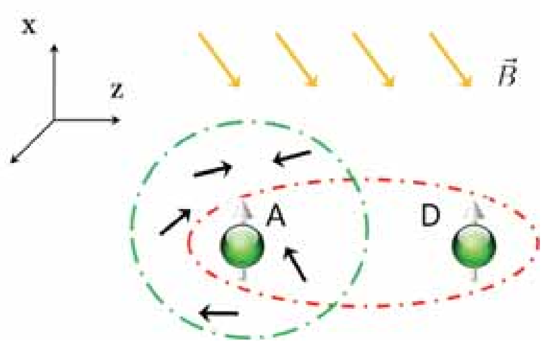


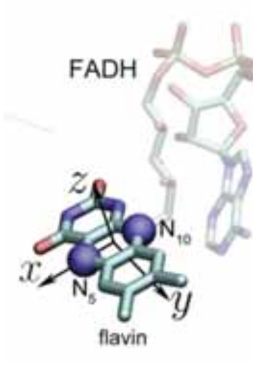
Reference-and-Probe model

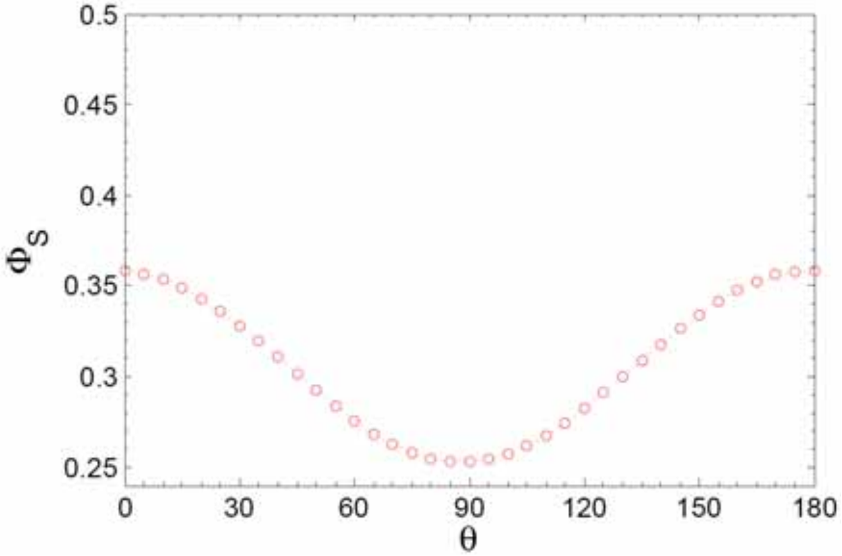
Marco Lanzagorta Quantum Technologies Group AIS - ITT Corporation (QuEBS 2010)

Design principles for a chemical compass

- Hyperfine coupling





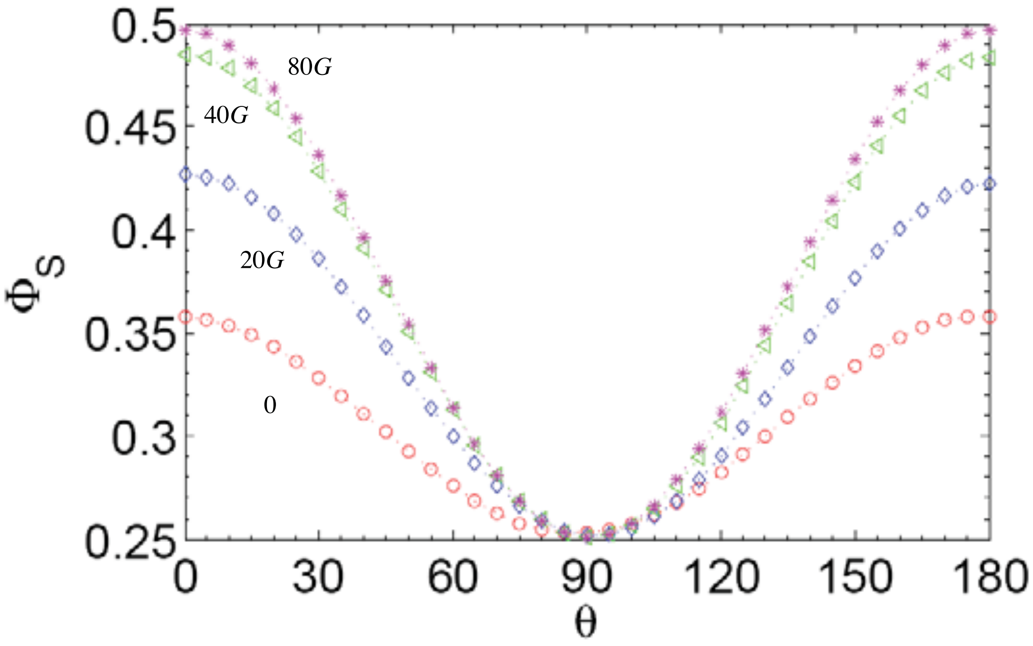


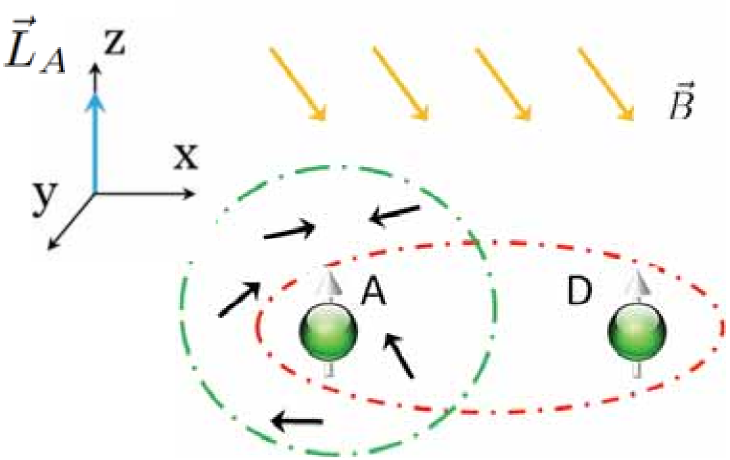
$$D_S = \Phi_S(\max) - \Phi_S(\min) \longrightarrow 12\%$$

Gradient field enhanced magnetic sensitivity

- Imbalanced local fields JMC, PRL (2011)

$\vec{B}_A = \vec{B} + \vec{L}_A$ $\vec{B}_D = \vec{B}$





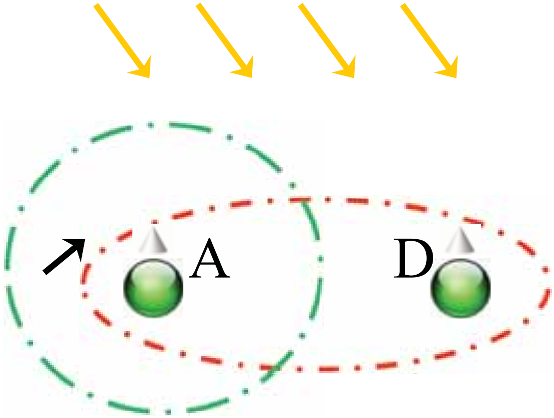
$$D_S = \Phi_S(\max) - \Phi_S(\min)$$

$$12\% \rightarrow 25\%$$

❖ Hybrid metal-chemical compass with a high magnetic sensitivity

❖ Large gradient field also increases the robustness of a chemical compass against noise

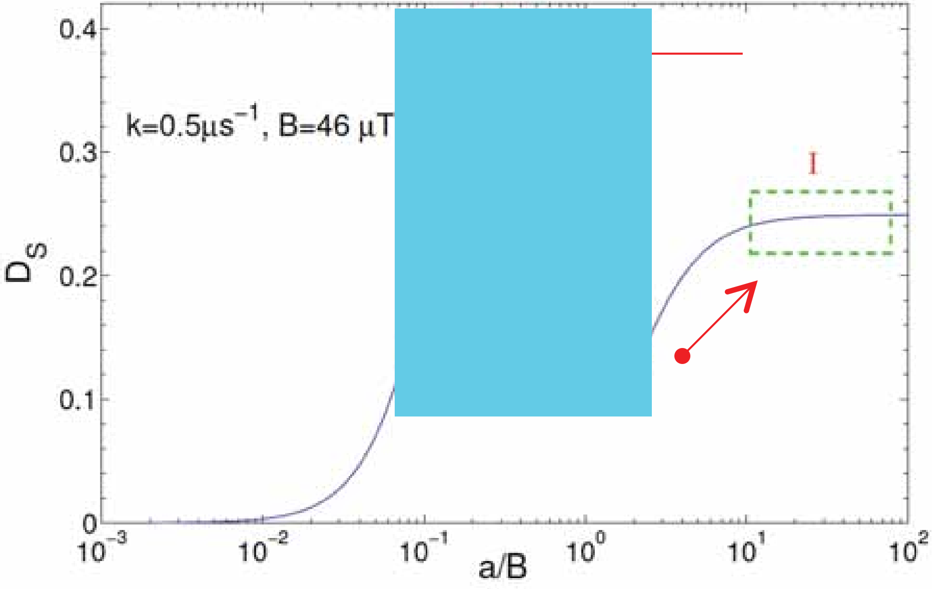
Magnetic sensitivity limit of a chemical compass

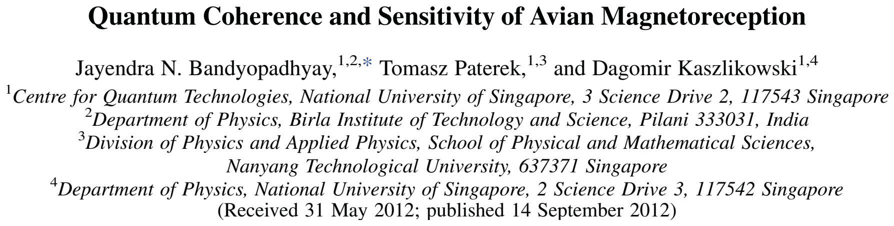


$$D_S = \Phi_S(\max) - \Phi_S(\min)$$

JMC, F. Caruso, M. B. Plenio, Phys. Rev. A 85, 040304(R) (2012)

- One nuclear spin is sufficient to give the best magnetic sensitivity





Quantum Coherence and Sensitivity of Avian Magnetoreception

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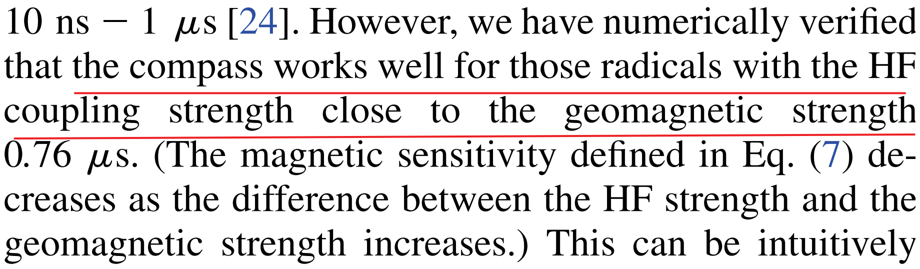
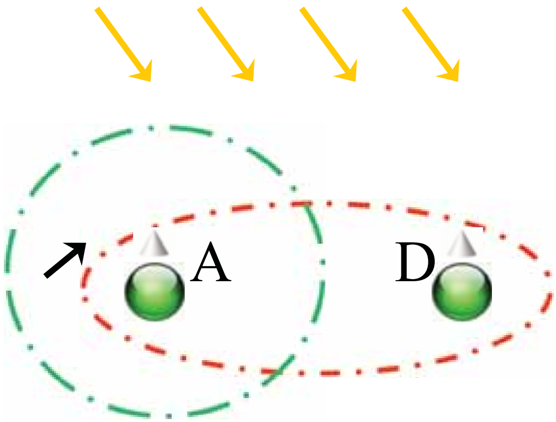
(Received 31 May 2012; published 14 September 2012)



10 ns − 1 μs [24]. However, we have numerically verified that the compass works well for those radicals with the HF coupling strength close to the geomagnetic strength 0.76 μs. (The magnetic sensitivity defined in Eq. (7) decreases as the difference between the HF strength and the geomagnetic strength increases.) This can be intuitively

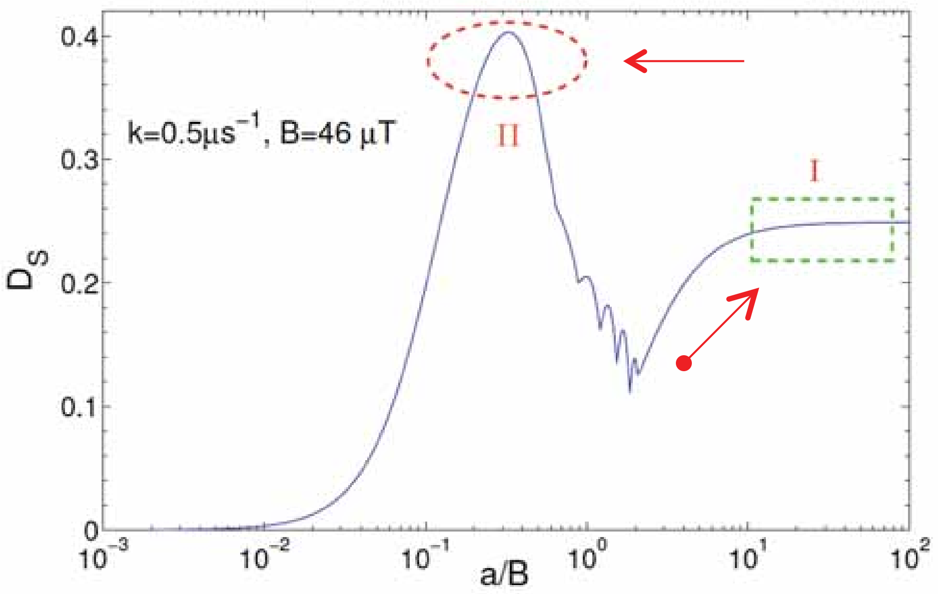
Magnetic sensitivity limit of a chemical compass

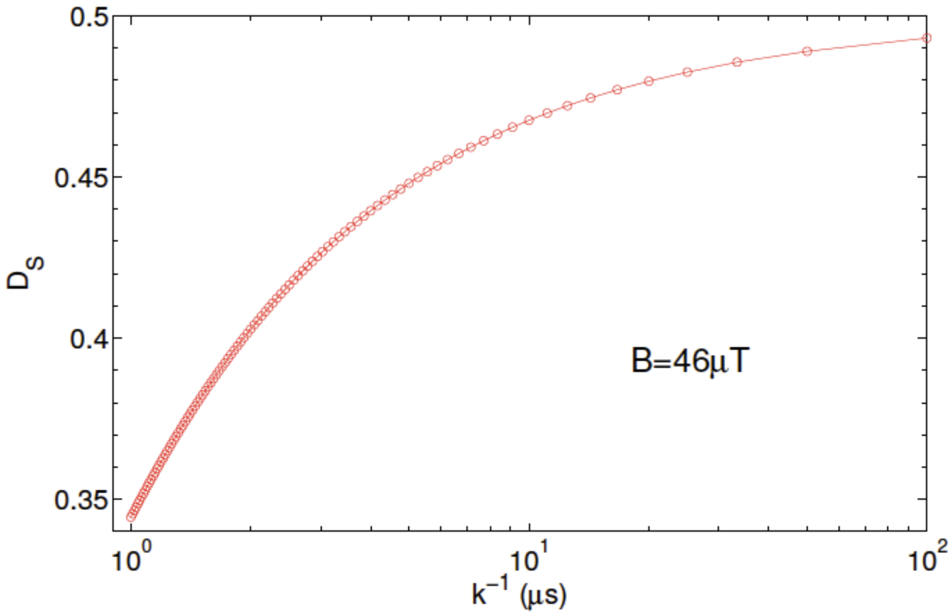


$$D_S = \Phi_S(\max) - \Phi_S(\min)$$

JMC, F. Caruso, M. B. Plenio, Phys. Rev. A 85, 040304(R) (2012)

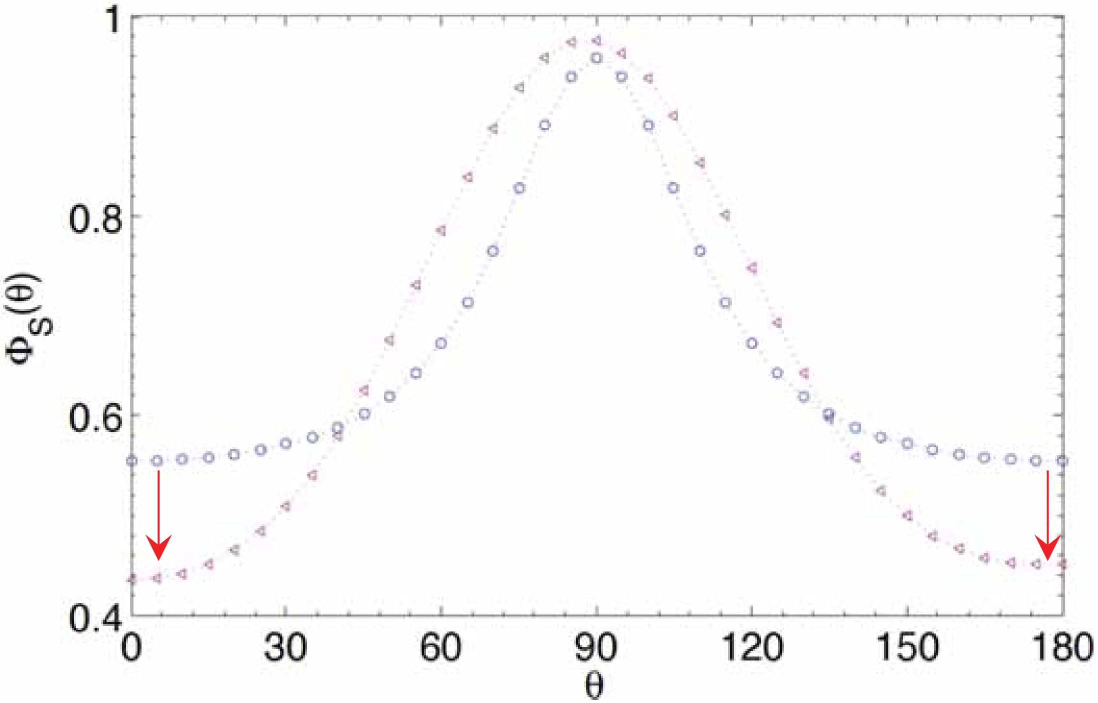
- One nuclear spin is sufficient to give the best magnetic sensitivity





Extend sensitivity limit of a chemical compass with quantum control

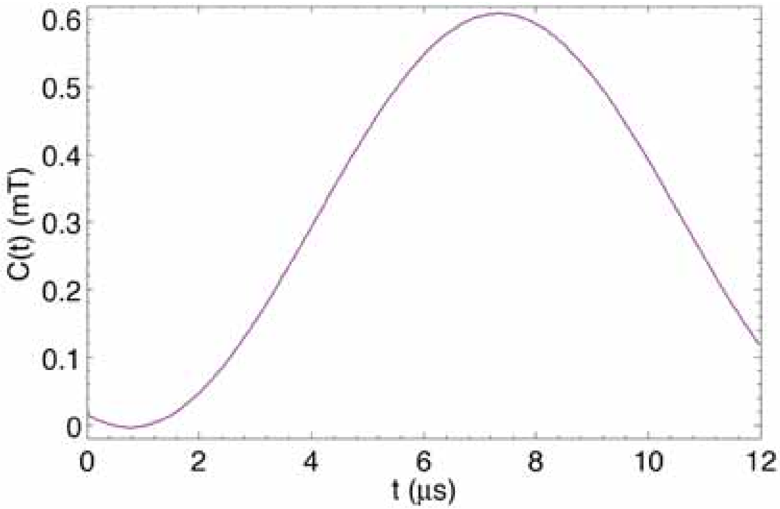
- Singlet product of an optimal chemical compass



$$40\% \rightarrow 55\%$$

- Continuous magnetic control field:

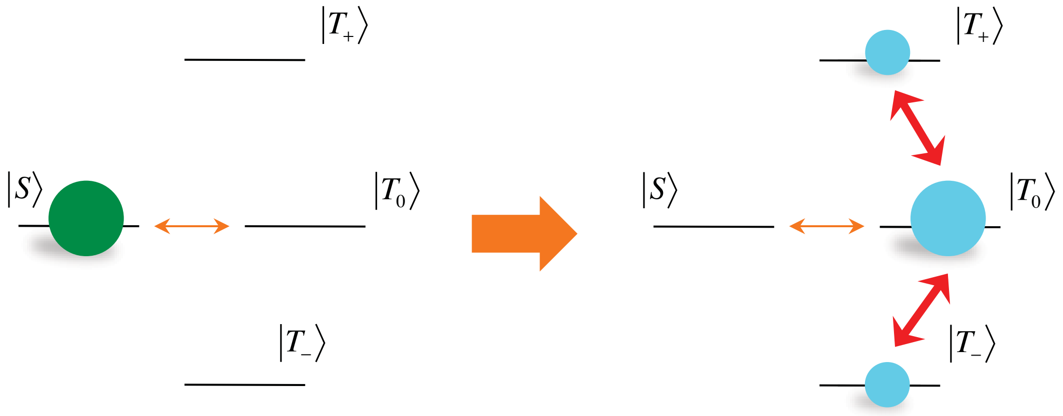
$$C(t) = \sum_k A_k \sin(\omega_k t) + B_k \cos(\omega_k t)$$

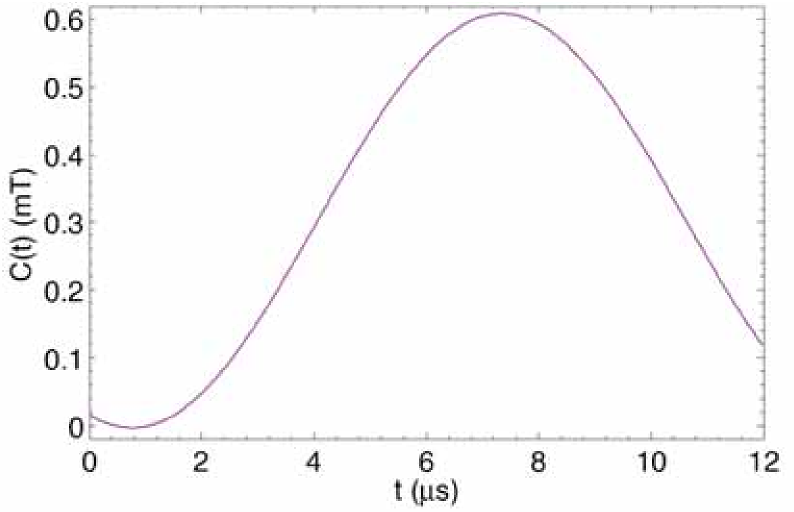


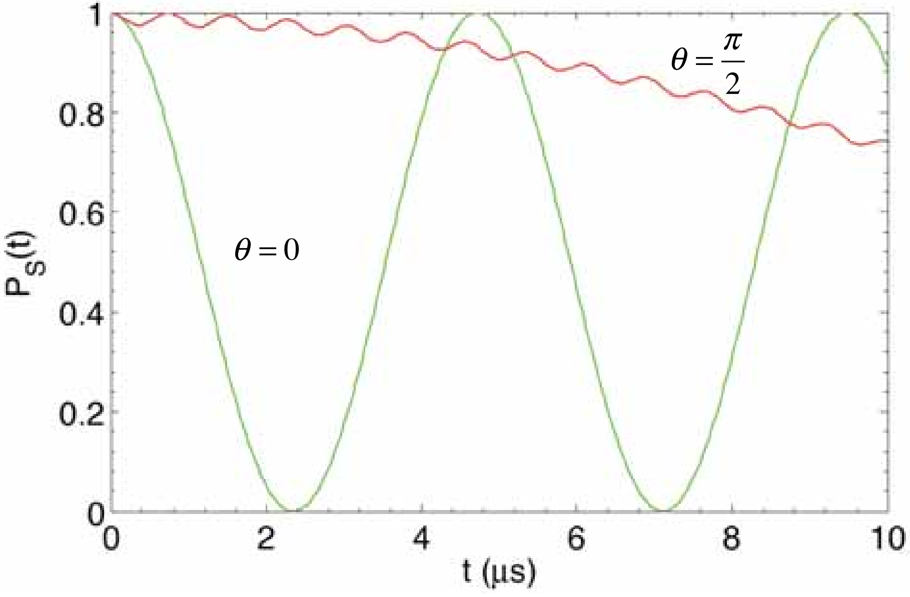
$$\omega_1 \approx 10kHz, \omega_2 \approx 80kHz$$

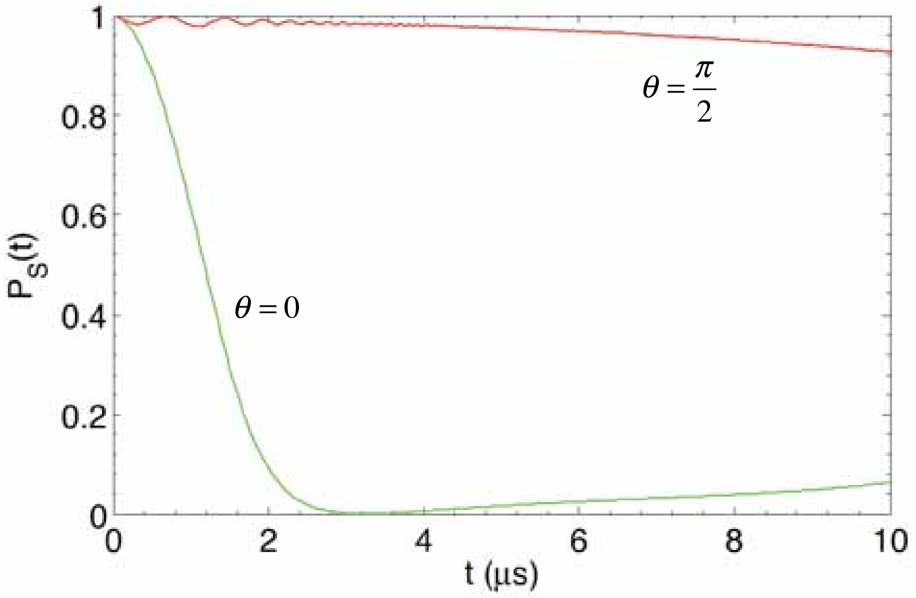
JMC, F. Caruso, M. B. Plenio, Phys. Rev. A 85, 040304(R) (2012)

Extend sensitivity limit of a chemical compass with quantum control







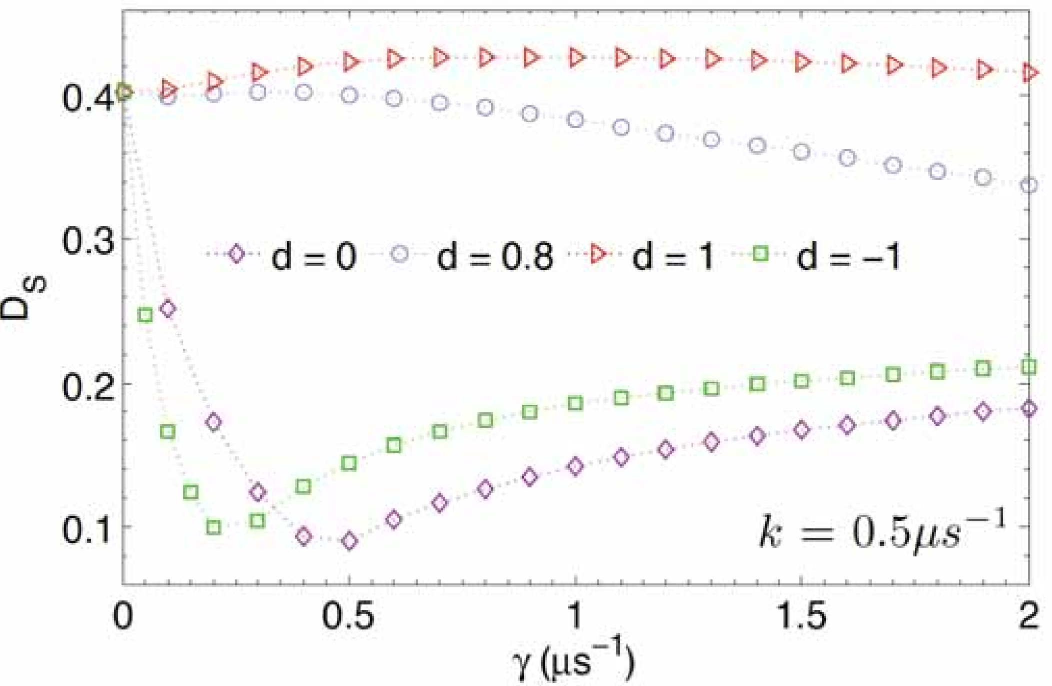


Quantum decoherence can be good for a chemical compass

- Pure dephasing:

$$D_S = \Phi_S(\max) - \Phi_S(\min)$$

$$\mathcal{L}_P(\rho) = \frac{1}{4} \sum_{k=1,2} \left(2 L_k \rho L_k^\dagger - L_k^\dagger L_k \rho - \rho L_k^\dagger L_k \right)$$



$$L_1 = \left(\frac{\gamma}{1+d^2}\right)^{1/2} \left[\sigma_z^{(1)} + d\sigma_z^{(2)}\right]$$

$$L_2 = \left(\frac{\gamma}{1+d^2}\right)^{1/2} \left[d\sigma_z^{(1)} + \sigma_z^{(2)}\right]$$

Coherent dynamics ⟷ dephasing

- Robust against correlated dephasing
- Increasing (anti) uncorrelated dephasing rate can recover magnetic sensitivity

Summary

- How do quantum feature/entanglement exist in a chemical compass?

- How to verify quantum effect in a chemical compass?

  - *Estimate quantum correlation/entanglement of radical pair spin states*

- How to design an artificial chemical compass?

  - *Design a bio-mimetic weak magnetic field sensor*

  - *Understand quantum features responsible for its magnetic sensitivity*

It is unclear whether quantum coherence/entanglement is essential for avian magnetoreception?

Thank you very much for your attention!