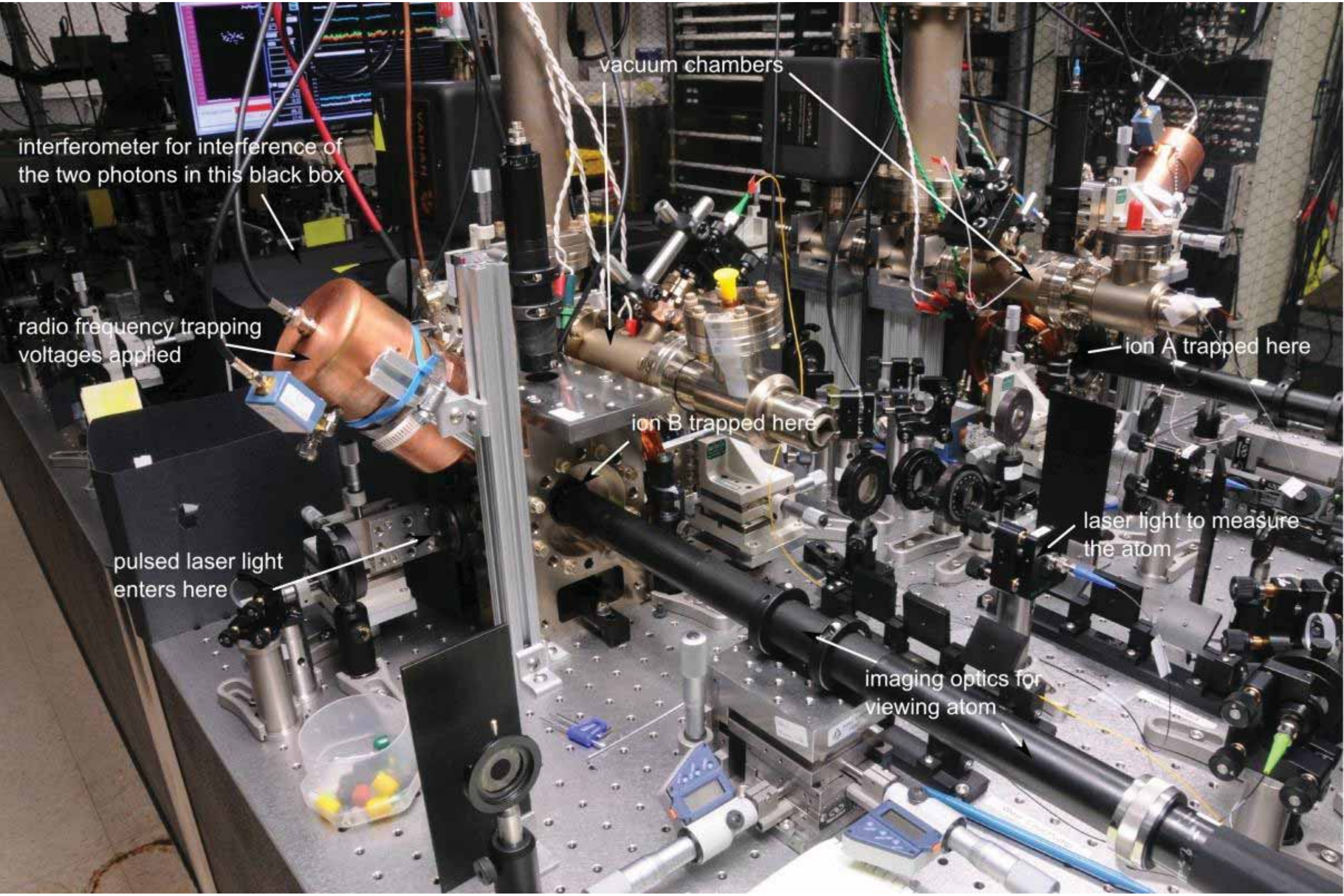
Animal magnetoreception and radical pair mechamism

Jianming Cai

Institute of Theoretical Physics, Universität Ulm

2013-03-01

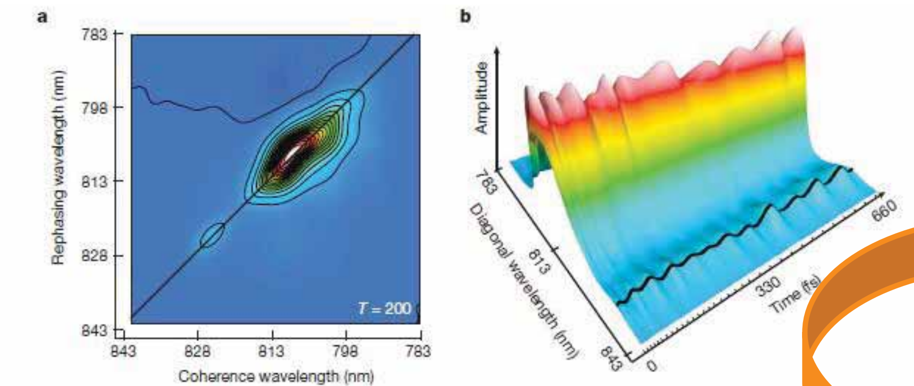

vacuum chambers
interferometer for interference of
the two photons in this black box
radio frequency trapping
voltages applied
ion A trapped here
ion B trapped here
laser light to measure
the atom
pulsed laser light
enters here
imaging optics for
viewing atom

nature Vol 446|12 April 2007|doi:10.1038/nature05678

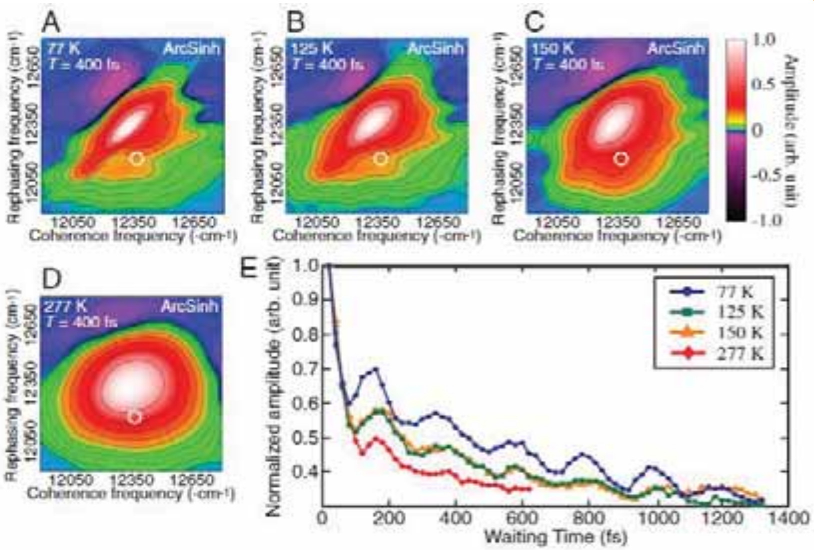
LETTERS

Evidence for wavelike energy transfer through quantum coherence in photosynthetic systems

Gregory S. Engel[1,2], Tessa R. Calhoun[1,2], Elizabeth L. Read[1,2], Tae-Kyu Ahn[1,2], Tomáš Mančal[1,2]†, Yuan-Chung Cheng[1,2], Robert E. Blankenship[3,4] & Graham R. Fleming[1,2]



Experimental evidence at cryogenic and physiological temperatures indicates the presence of quantum coherence



PNAS

www.pnas.org/cgi/doi/10.1073/pnas.1005484107

Long-lived quantum coherence in photosynthetic complexes at physiological temperature

Gitt Panitchayangkoon[a], Dugan Hayes[a], Kelly A. Fransted[a], Justin R. Caram[a], Elad Harel[a], Jianzhong Wen[b], Robert E. Blankenship[b], and Gregory S. Engel[a,1]

[a]Department of Chemistry and The James Franck Institute, University of Chicago, Chicago, IL 60637; and [b]Departments of Biology and Chemistry, Washington University, St. Louis, MO 63130

Other results: Scholes (Toronto), van Hulst (ICFO)...

REVIEW ARTICLE
PUBLISHED ONLINE: 9 DECEMBER 2012 | DOI: 10.1038/NPHYS2474

nature physics

Quantum biology

Neill Lambert[1]★, Yueh-Nan Chen[2], Yuan-Chung Cheng[3], Che-Ming Li[4], Guang-Yin Chen[2] and Franco Nori[1,5]★

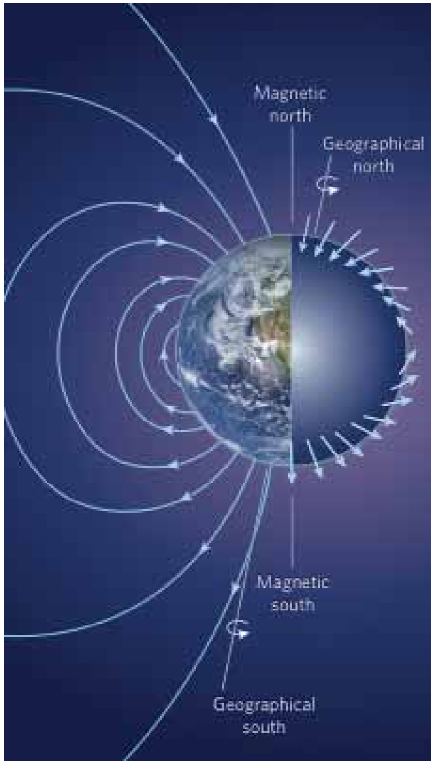
Recent evidence suggests that a variety of organisms may harness some of the unique features of quantum mechanics to gain a biological advantage. These features go beyond trivial quantum effects and may include harnessing quantum coherence on physiologically important timescales. In this brief review we summarize the latest results for non-trivial quantum effects in photosynthetic light harvesting, avian magnetoreception and several other candidates for functional quantum biology. We present both the evidence for and arguments against there being a functional role for quantum coherence in these systems.

Table 1 | Summary of a selection of the main experimental and theoretical works on functional quantum biology.

Biological system		Reference
Photosynthesis	Cryogenic-temperature quantum coherence	12,14
	Ambient/room-temperature quantum coherence (FMO)	16
	Ambient/room-temperature quantum coherence (algae)	15
	Environment-assisted transport	19,26,27,29
	Entanglement, tests of quantumness	48,49,103
	Alternative views	46,47,51
Radical-pair magnetoreception	Early proposals and evidence	60,66
	Mathematical models	66,67
	Indirect evidence (light dependence, magnetic field)	58,61,64,65,78,104
	Experiments on radical pairs	7,71–73,105
Other examples	Olfaction	92,93
	Vision	97,99
	Long-range electron transfer	81,82
	Enzyme catalysis	84,85

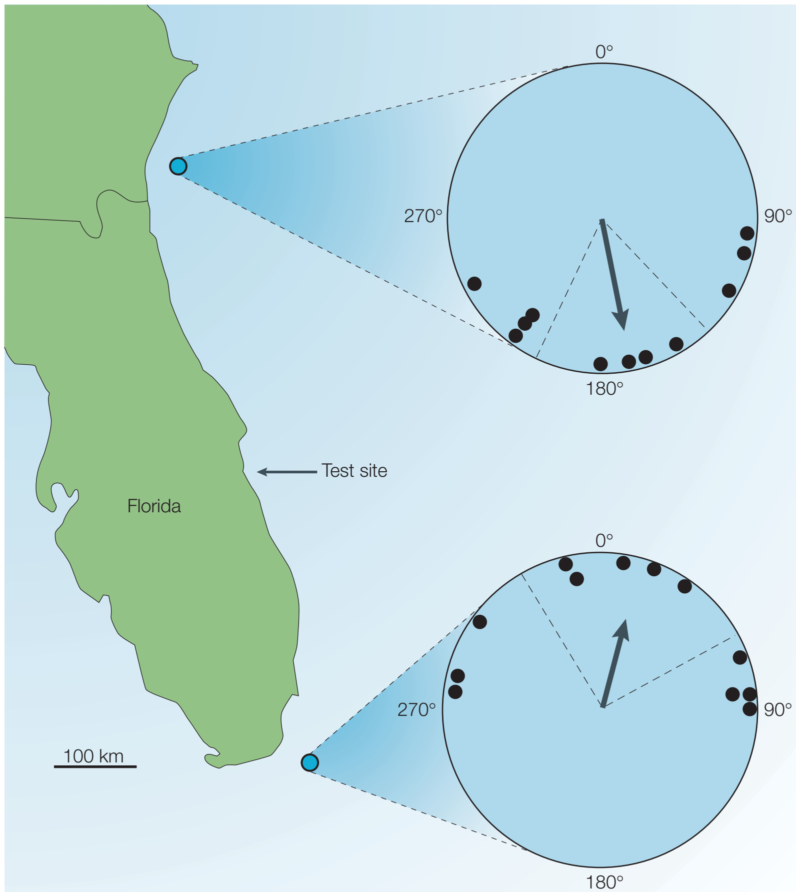
Magnetoreception in Animals

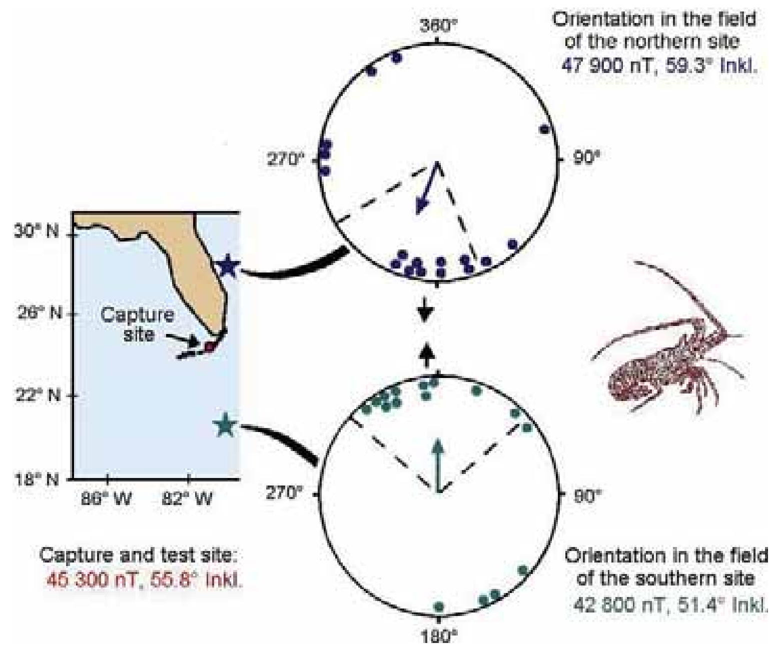
Magnetoreception found in a wide variety of animals: migratory birds, see turtles, bats, newts, lobsters, bees, fruitfries, bacteria ...



Kenneth J. Lohmann, Nature (2010)

Magnetoreception in Animals





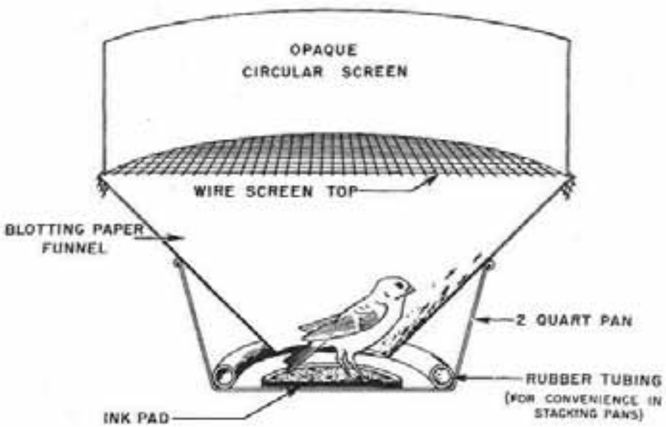
Kenneth J. Lohmann, Nature (2010)

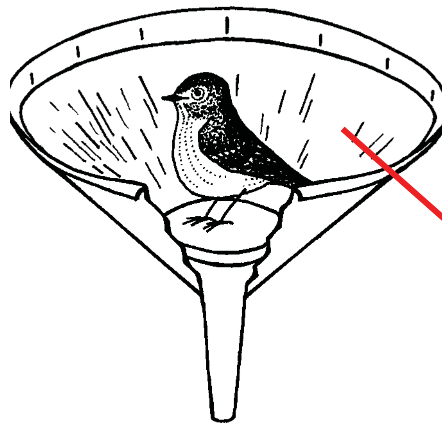
Avian Magnetoreceptionn

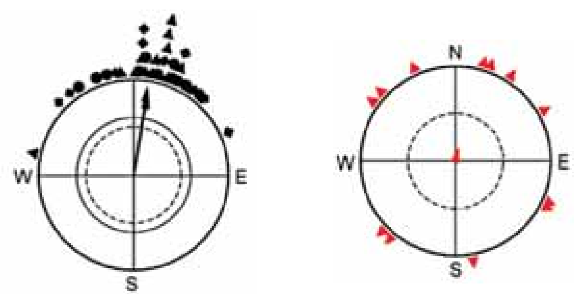
Migratory birds use the Earths magnetic field to orient themselves during migration

Captive birds are so eager to migrate that they will orient themselves in a cage in the direction they wish to fly.

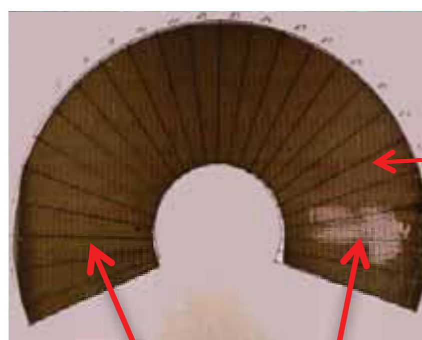
R. Wiltschko & W. Wiltschko







each triangle represents the orientation of one bird



Scratches

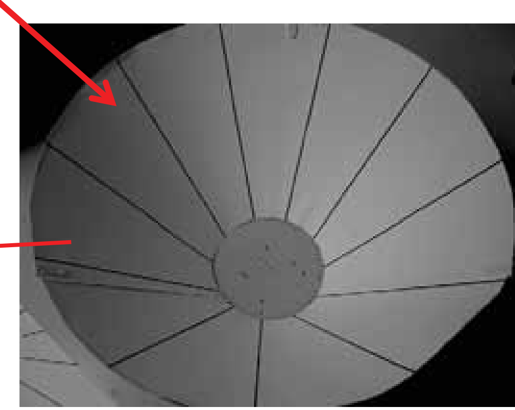
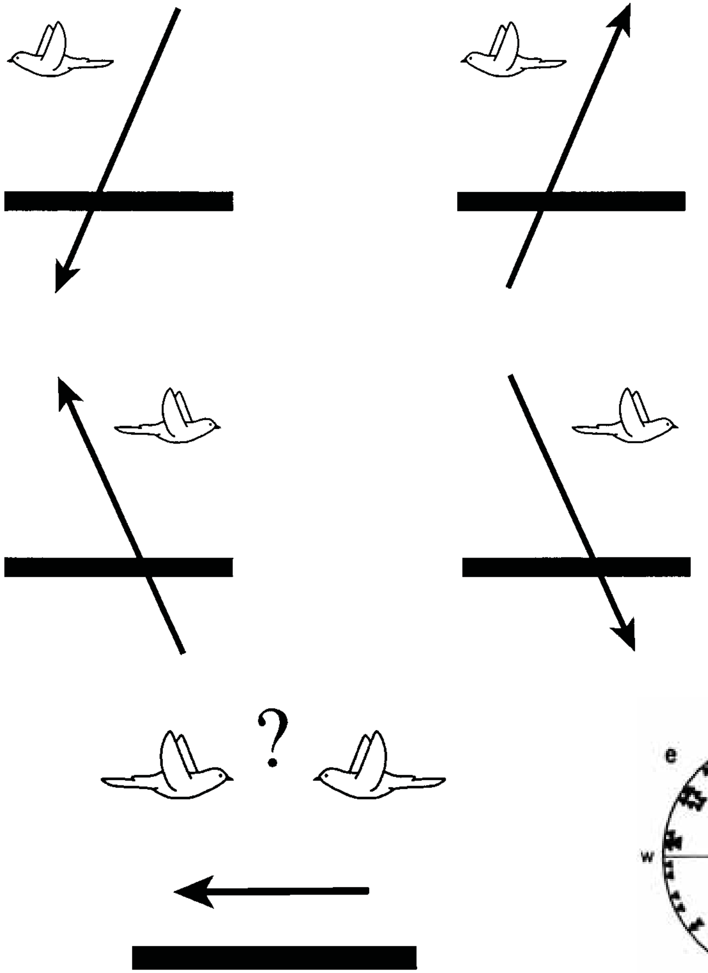


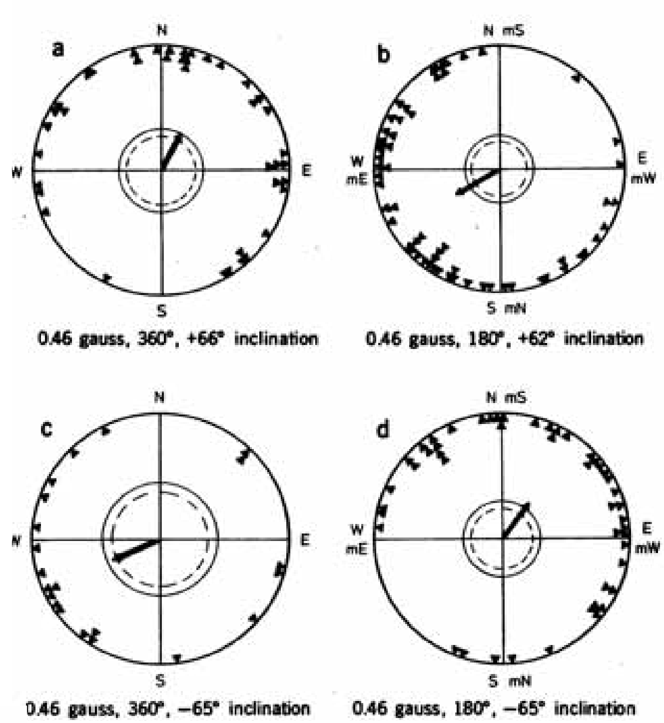
Figure 3. Funnel Cage Lined with Coated Paper Carrying Radial Lines Provide Visual Features

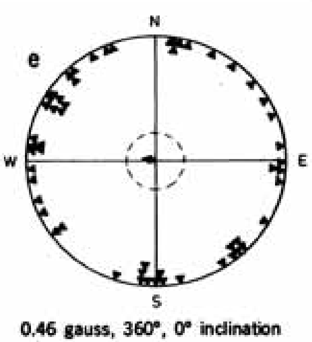
Avian compass is an inclination compass

Inclination compass: **Birds must know the direction of up to differentiate North from South**

Perception depends only on the inclination of the field lines, not the polarity.







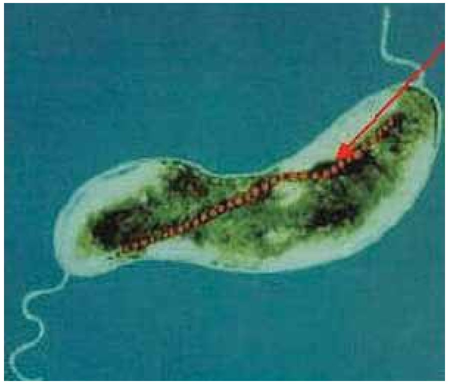
R. Wiltschko & W. Wiltschko

Henrik Mouritsen

Two Models for Avian Magnetoreceptionn

1. Use of Magnetic particle

Naval Research Laboratory (NRL)



The idea was inspired in part by the discovery that some bacteria produce magnetite crystals; as a result, the bacteria are physically rotated into alignment with geomagnetic field lines and can move along them.

Indeed magnetite has been found in birds but it does not explain key observations

2. Radical pair mechanism

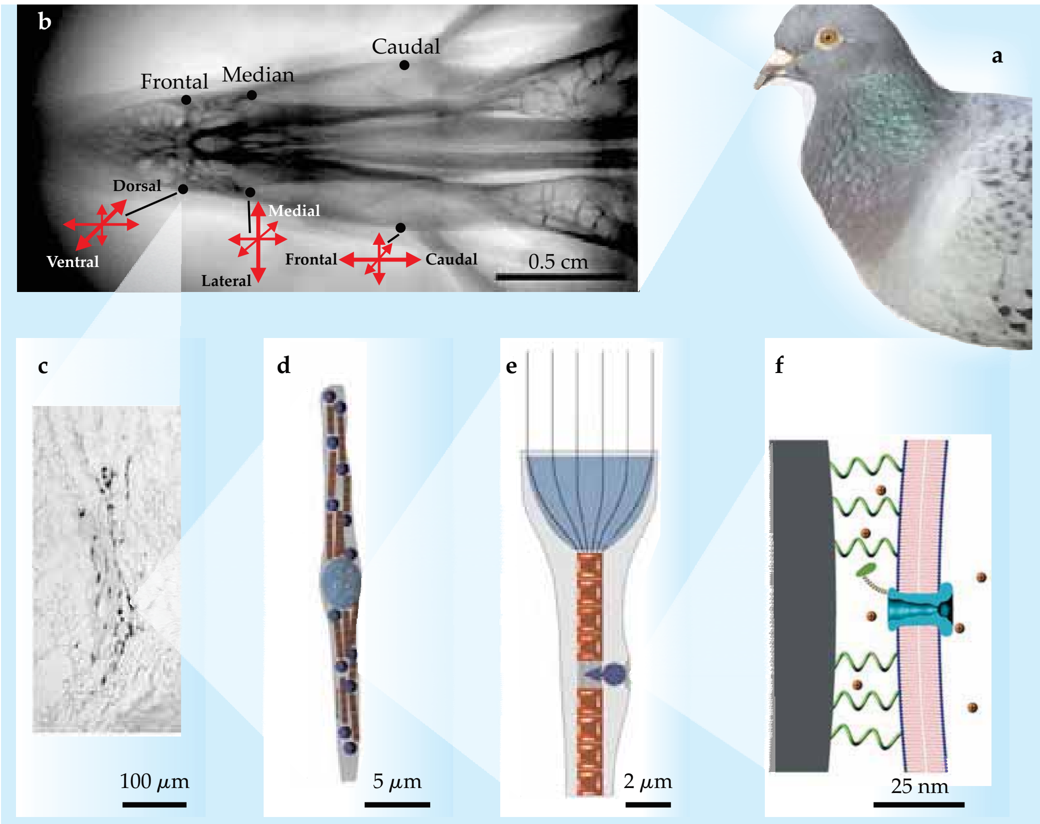
It was a biochemical mechanism discovered in spin chemistry more than 40 years ago and has gain supporting evidences by experiments.

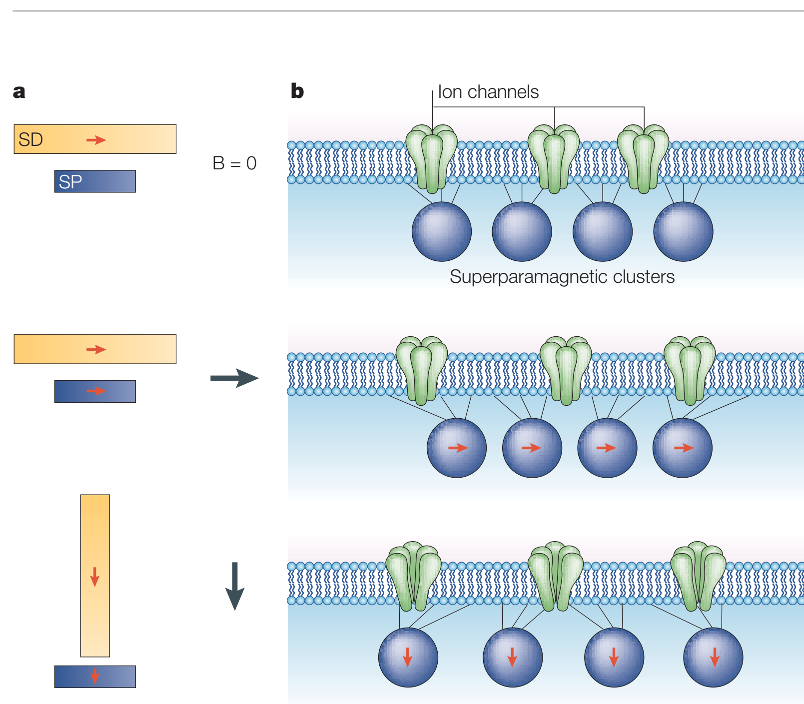
The principle is that magnetoreception occurs through unusual biochemical reactions that are influenced by Earth's magnetic field. The proposed reactions involve pairs of free radicals as fleeting intermediates, so the idea is also known as the radical-pairs hypothesis.

It is likely that birds use both mechanisms to construct a magnetic map.

Animal Magnetoreception: Use of Magnetic particle

Evidence for magnetite-based magnetoreception





Strong magnetic pulses cause birds and turtles randomize the preferred orientation direction

Johnsen and Lohmann, Nature reviews (2005)

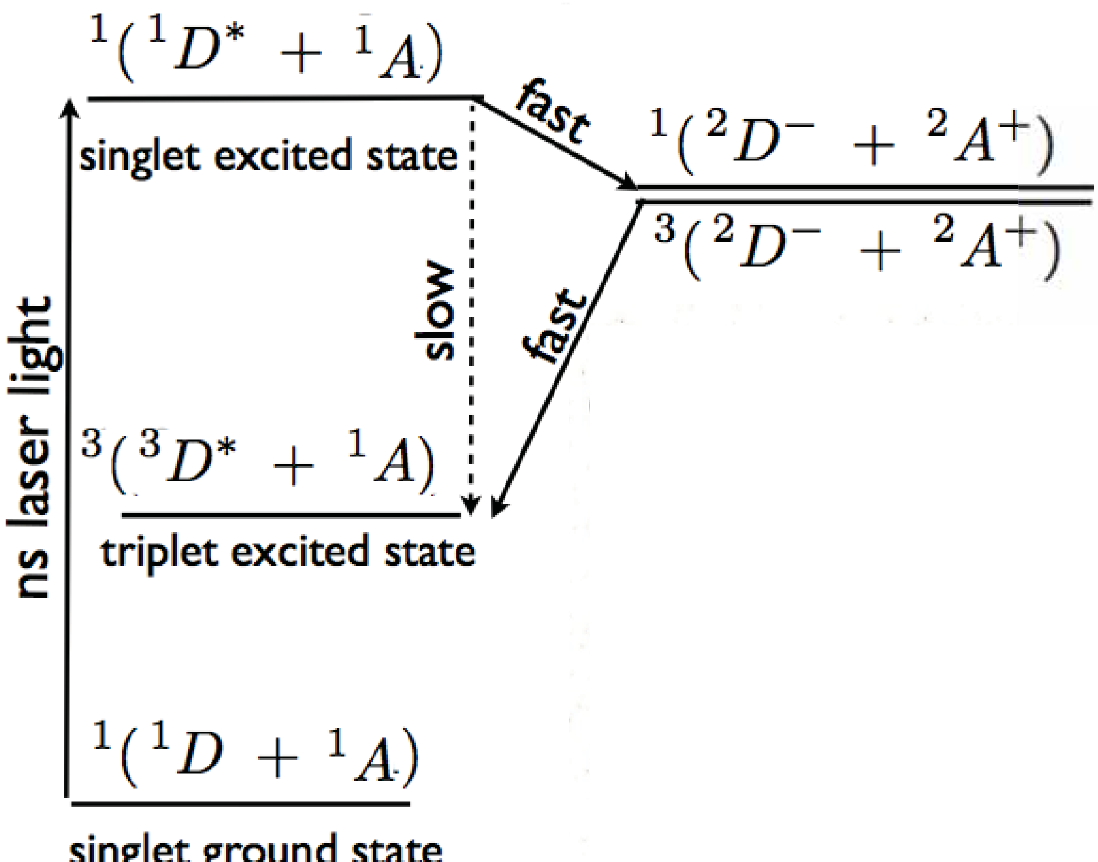
Avian Magnetoreception: Radical pair mechanism

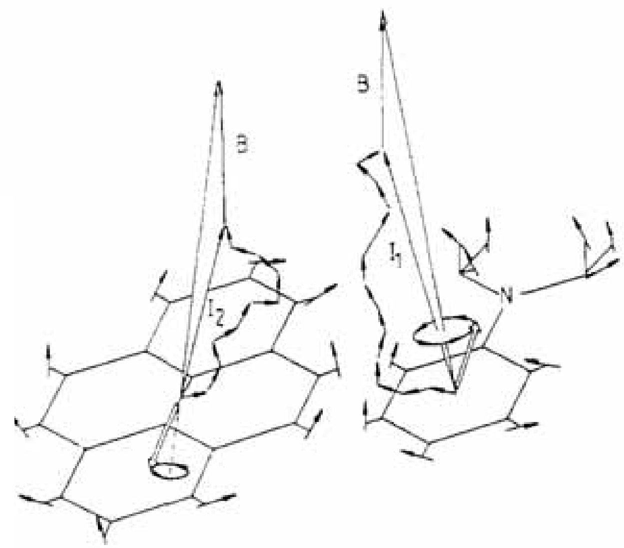
Theory of the magnetic field modulated geminate recombination of radical ion pairs in polar solvents: Application to the pyrene–*N*,*N*-dimethylaniline system

H.-J. Werner, Z. Schulten, and K. Schulten

Max-Planck-Institut für biophysikalische Chemie, Abt. Spektroskopie, D-3400 Göttingen, Federal Republic of Germany

(Received 11 January 1977)





e 4. Graphical representation of electron spin precession resultant effective magnetic fields of local hyperfine in- ons. Example of (pyrene)$^{\bullet-}$/(*N*,*N*-dimethylaniline)$^{\bullet+}$ radical Reprinted from ref 65 with kind permission of K. Schulten; ght 1978 American Institute of Physics.

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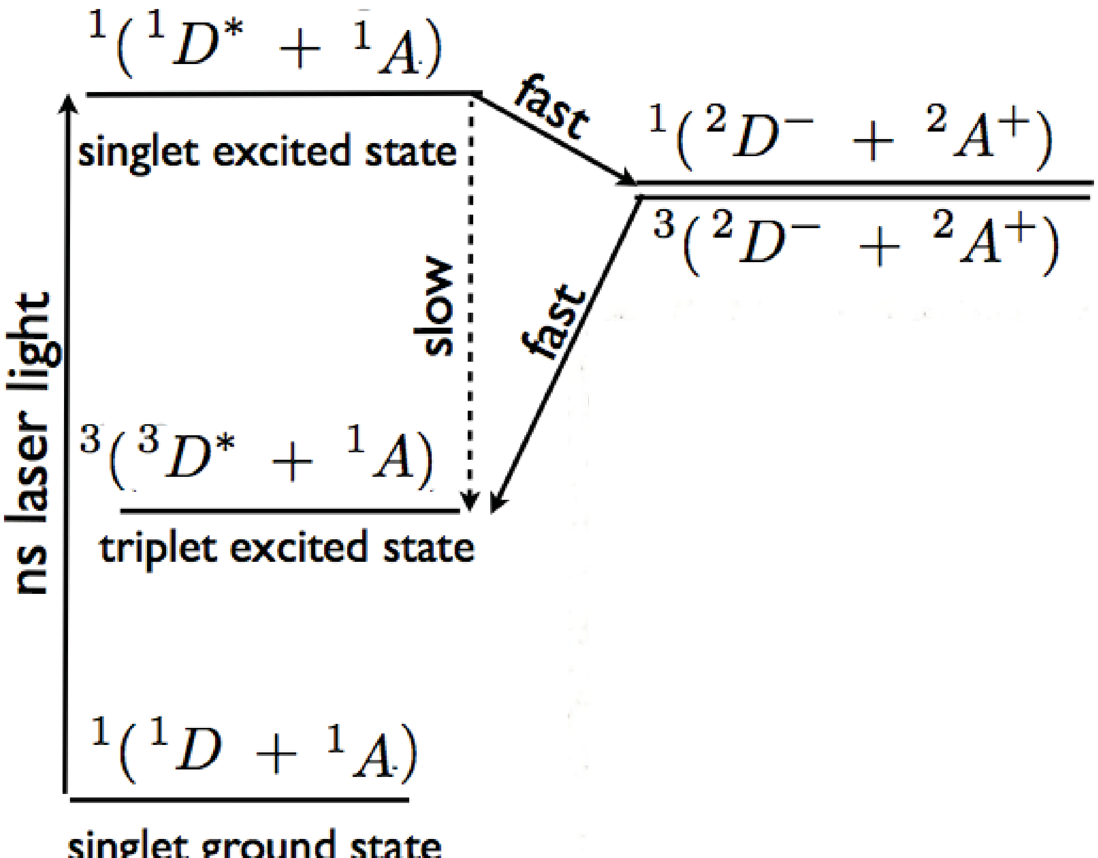

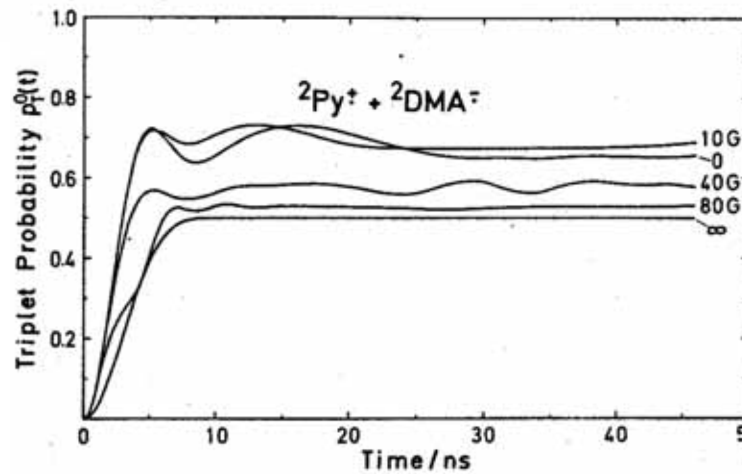

FIG. 1. Time evolution of the hyperfine-induced triplet probability $p_T^0(t)$ for the radical pair system $^2Py^{\bar{\cdot}} + {}^2DMA^{\dot{+}}$ for magnetic fields $B = 0$, 10, 40, 80 G and $B \to \infty$. The hyperfine coupling constants are given in the text.

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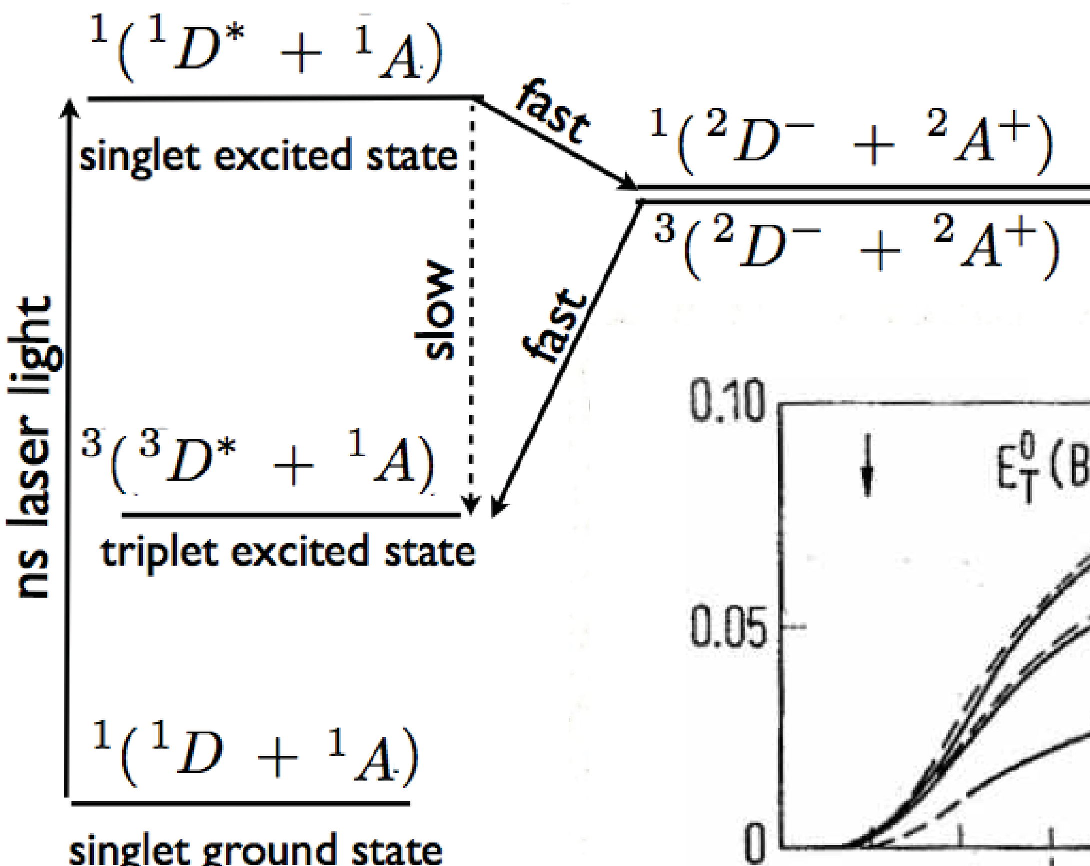
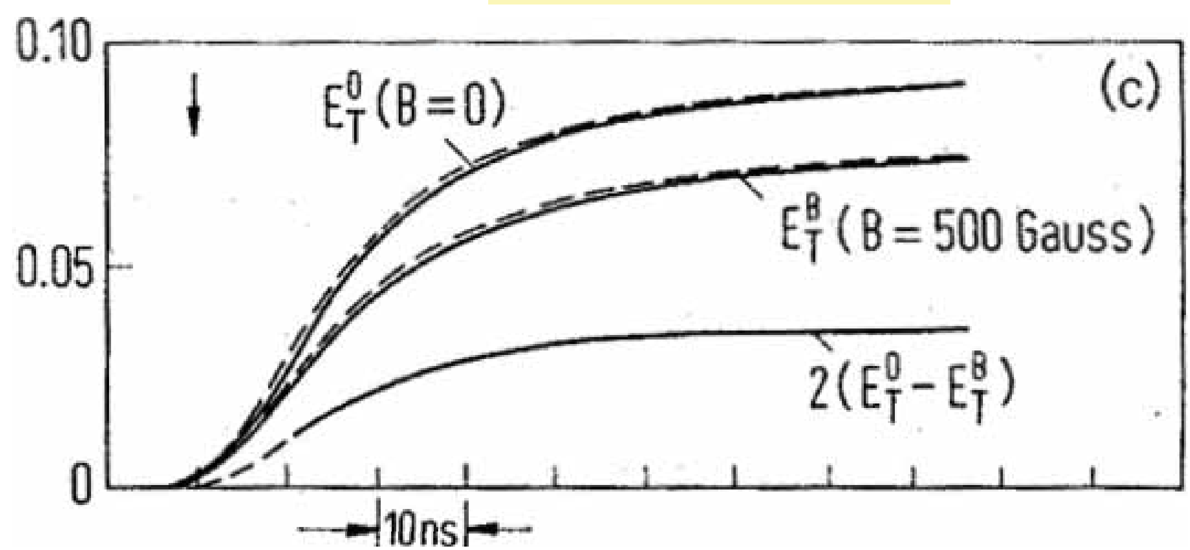
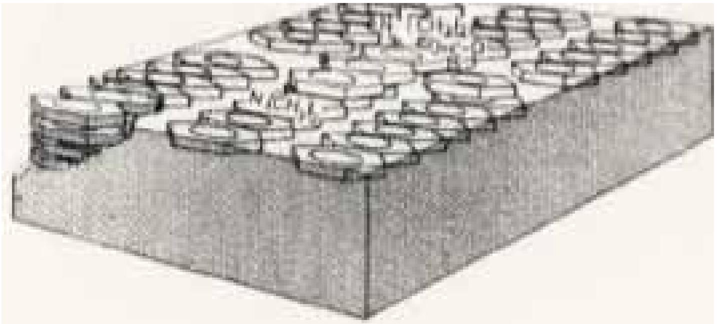


Magnetic field effect



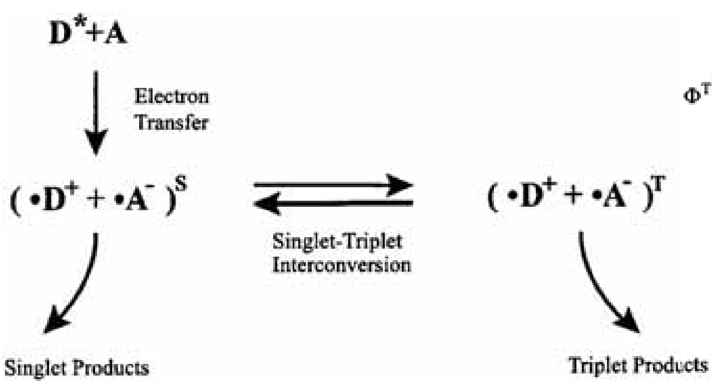
Avian Magnetoreception: Radical pair mechanism

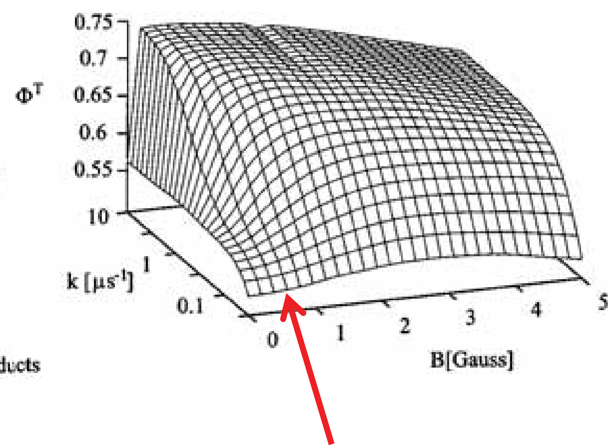
Biophysical Journal, 78:707-718, 2000

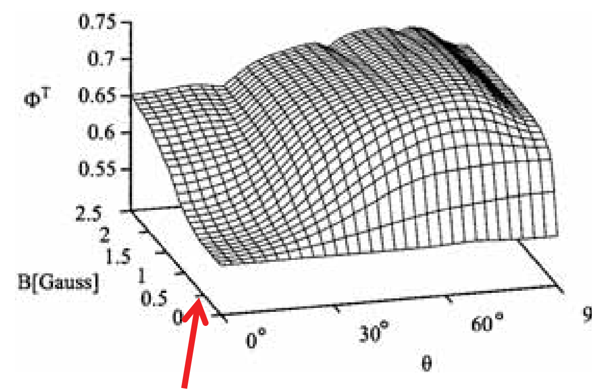


$$\mathbf{A}_1 = \begin{pmatrix} 10\text{ G} & 0 & 0 \\ 0 & 10\text{ G} & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\mathbf{A}_2 = \begin{pmatrix} 5\text{ G} & 0 & 0 \\ 0 & 5\text{ G} & 0 \\ 0 & 0 & 5\text{ G} \end{pmatrix}$$



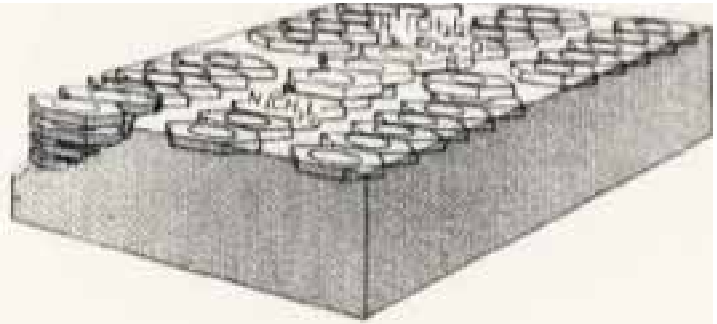




A chemical compass Should work in geo-magnetic field!

B=0.5 Gauss

Avian Magnetoreception: Radical pair mechanism



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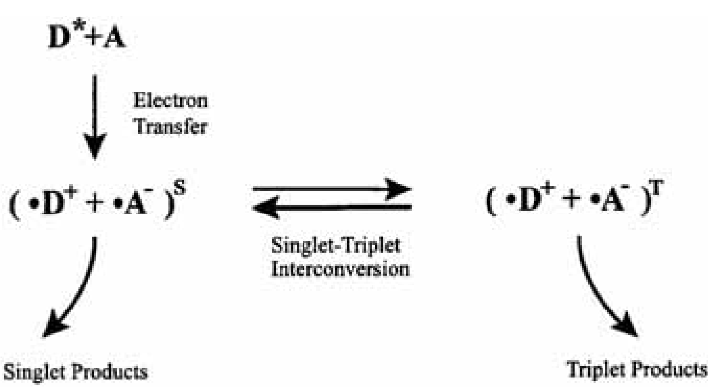


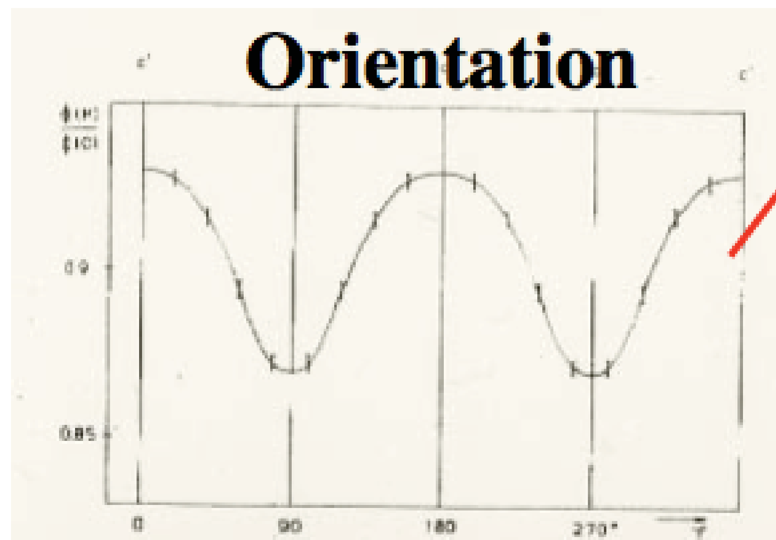
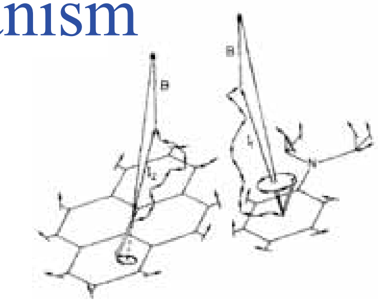


Fig. 3. Normalized magnetic field modulation of the sensitized delayed fluorescence ϕ as a function of the angle between the direction of the external magnetic field H and the c axis of the anthracene crystal

It is only an inclination compass!

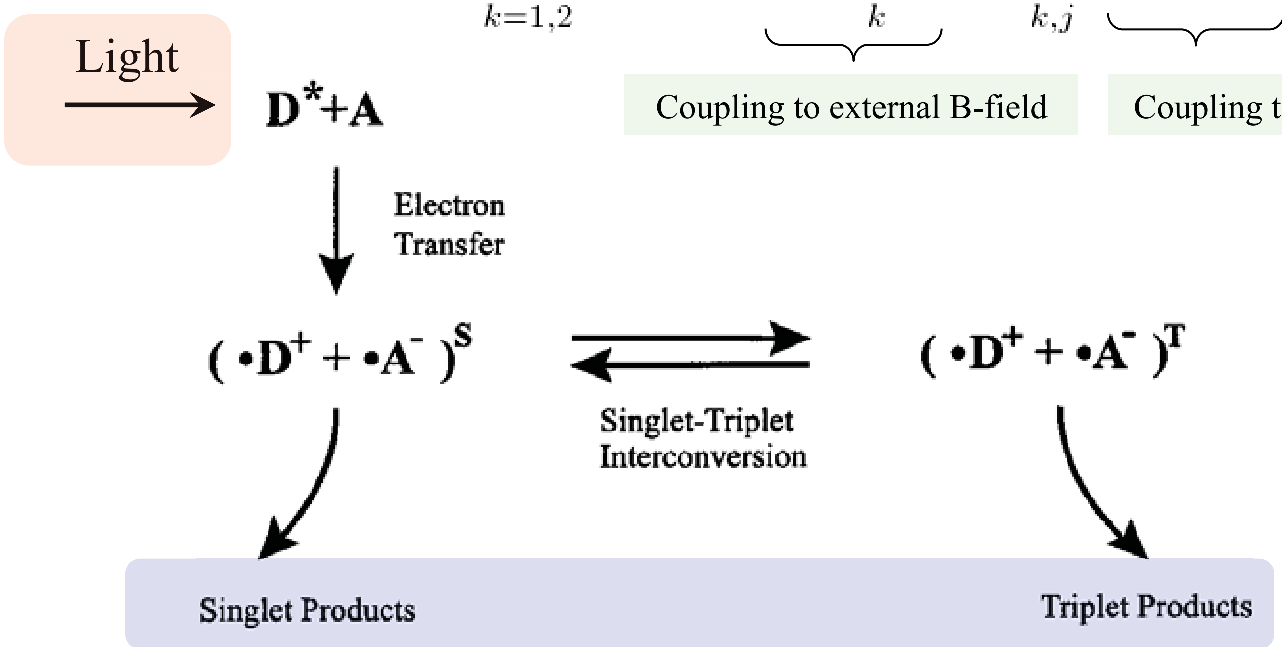
Avian Magnetoreception: Radical pair mechanism



$$H = \sum_{k=1,2} H_k = -\gamma_e \vec{B} \cdot \underbrace{\sum_k \vec{S}_k}_{} + \sum_{k,j} \underbrace{\vec{S}_k \cdot \hat{\lambda}_{k_j} \cdot \vec{I}_{k_j}}_{}$$

Coupling to external B-field

Coupling to local nuclear-spin envionment



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

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

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

Jyrki's talk

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

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

1. How is the signal processed: from the singlet and triplet products to biological signals?

2. Where is the magnetoreceptor?

Radical pair mechanism: needs light

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

Coupling to external B-field

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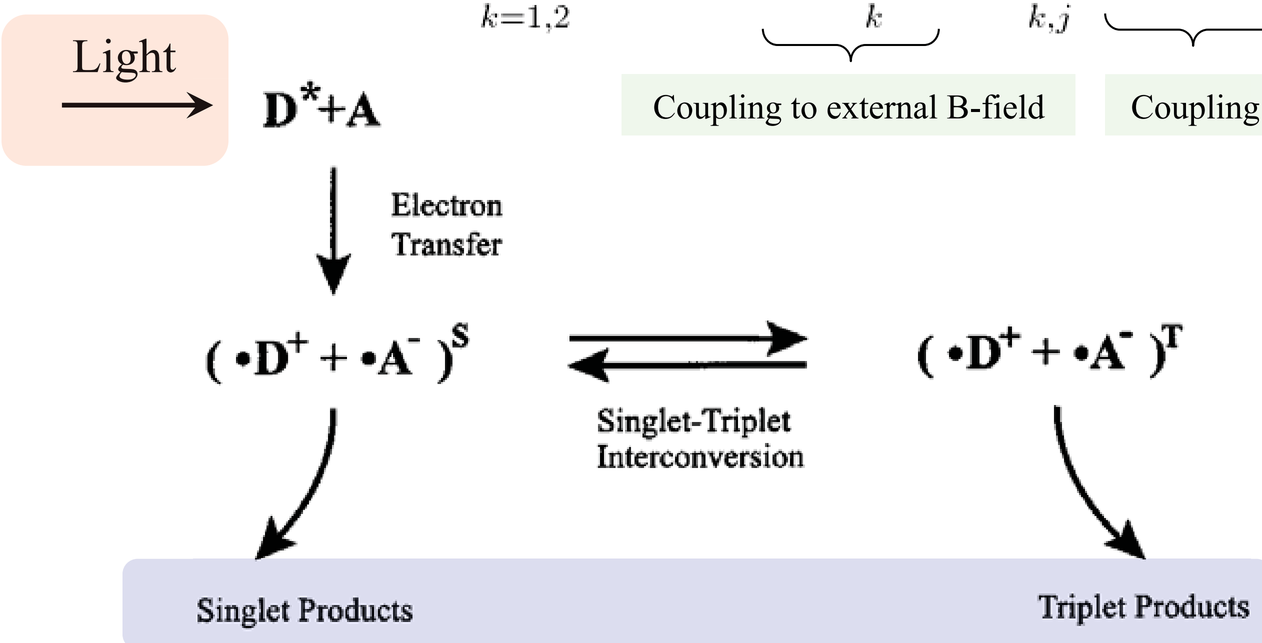
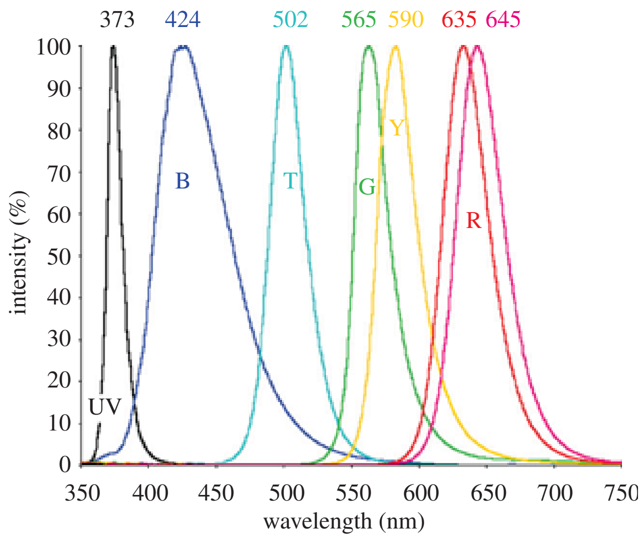
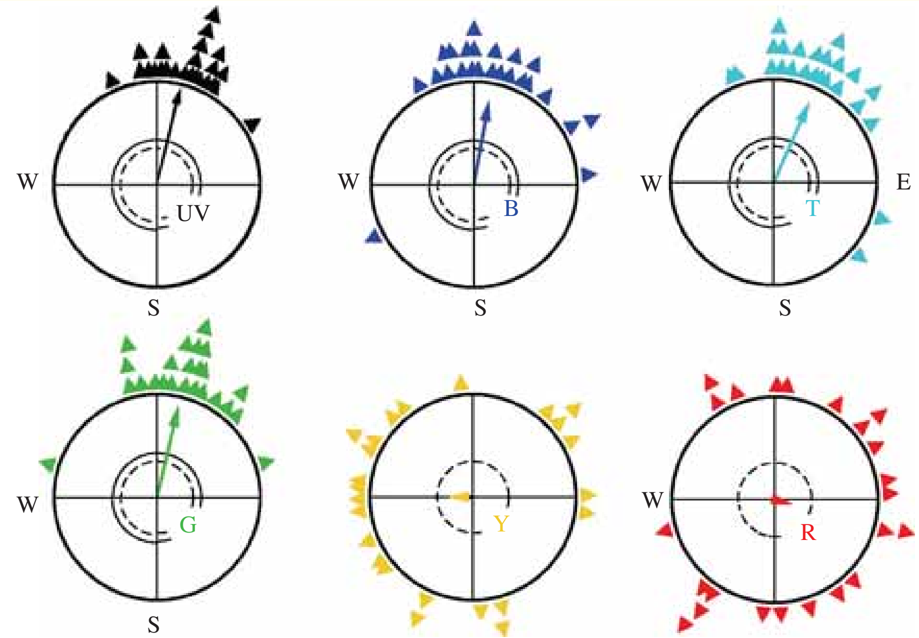


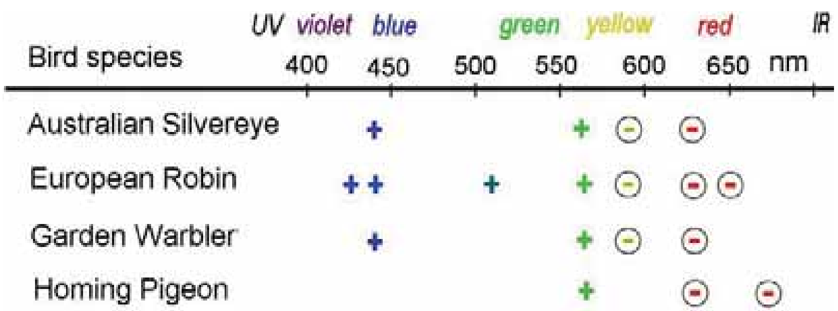
Avian compass is light-dependent

Light-dependent magnetoreception



Migrator birds requires light below a threshold wavelength to sense magnetic fields





1. Disoriented in darkness and in red or yellow light
2. Orient only in UV, blue and green light

Photoreceptor maybe involved

T. Ritz (2007)

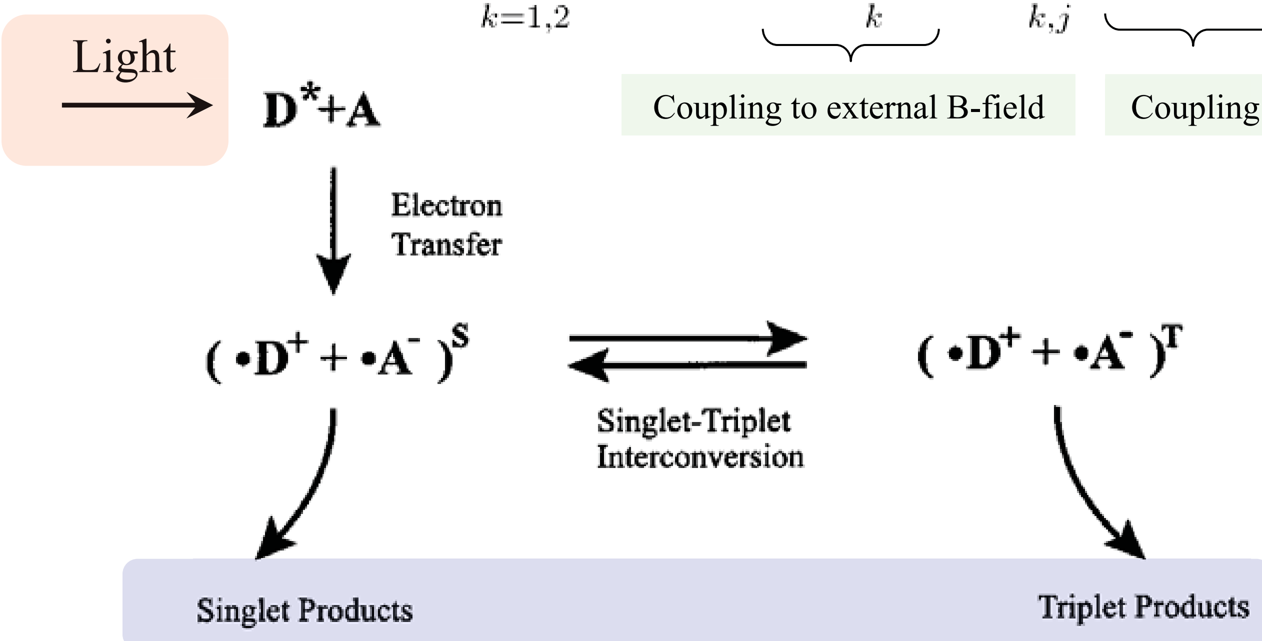
R. Wiltschko & W. Wiltschko

Radical pair mechanism: needs light

$$H = \sum_{k=1,2} H_k = -\gamma_e \vec{B} \cdot \underbrace{\sum_k \vec{S}_k}_{} + \sum_{k,j} \underbrace{\vec{S}_k \cdot \hat{\lambda}_{k_j} \cdot \vec{I}_{k_j}}_{}$$

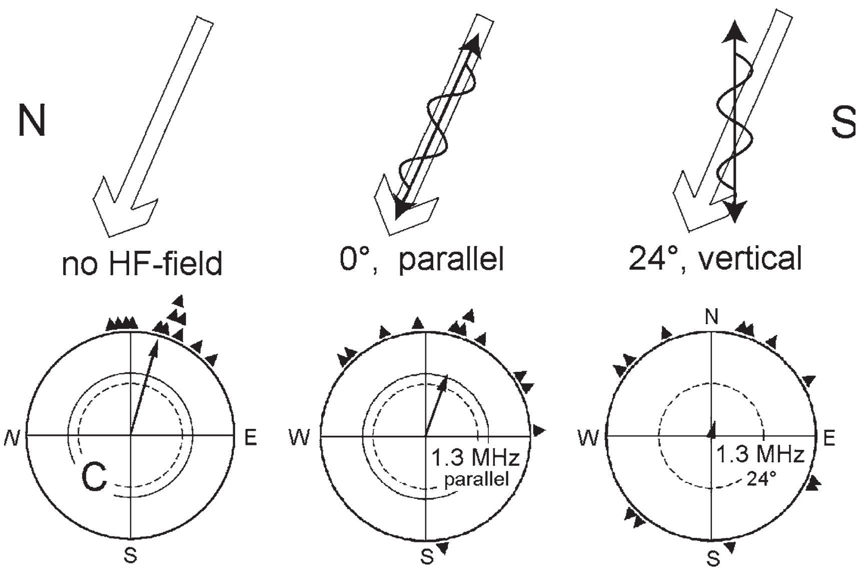
Coupling to external B-field

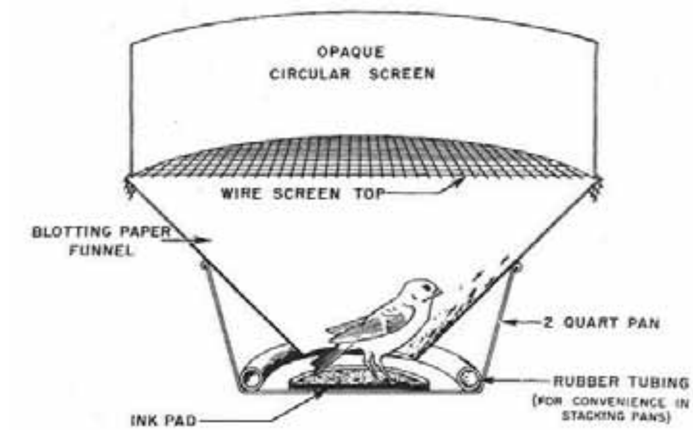
Coupling to local nuclear-spin envionment



Avian Magnetoreception: Resonance effects

Resonance experiments:





Intensity (nT)	46 μT static field								92 μT static field	
480	↗	↗	⤡	⤡	−	−	−	−		
150					↗		↗		↗	
48						−	↗		↗	−
15						−	↗			−
5						↗				↗
	0.01	0.03	0.1	0.5	0.65	1.315	2.63	7.0	1.315	2.63

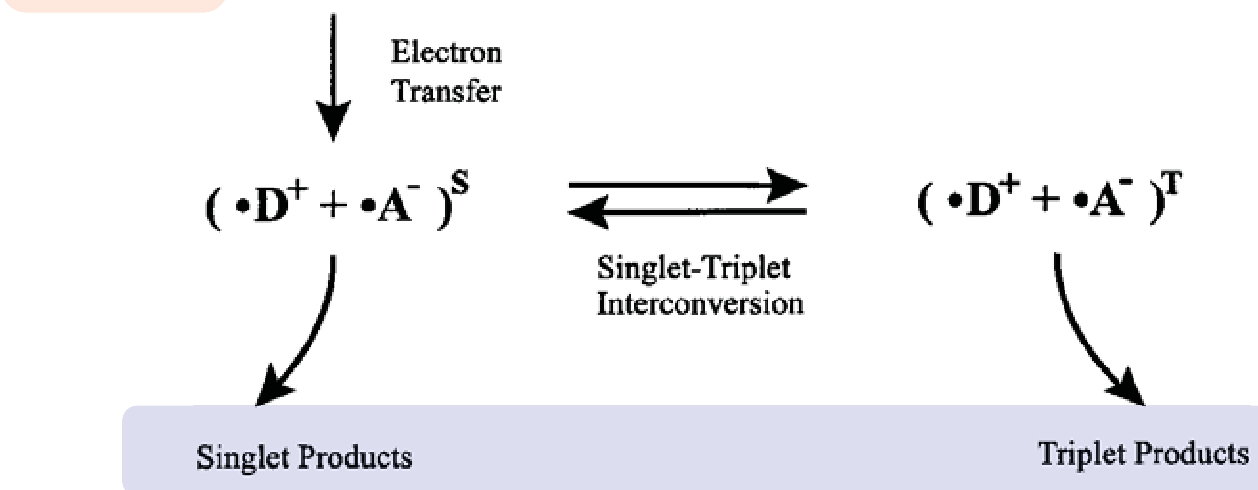
Frequency (MHz)

Probe-and-reference model

T. Ritz, R. Wiltschko & W. Wiltschko (2000)

Avian Magnetoreception: Radical pair mechanism

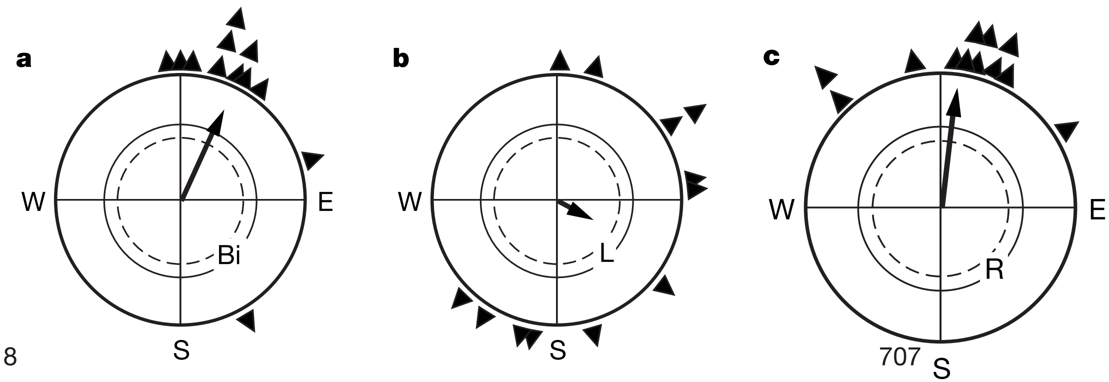
$$H = \sum_{k=1,2} H_k = -\gamma_e \underbrace{\vec{B} \cdot \sum_k \vec{S}_k}_{\text{Coupling to external B-field}} + \sum_{k,j} \underbrace{\vec{S}_k \cdot \hat{\lambda}_{k_j} \cdot \vec{I}_{k_j}}_{\text{Coupling to local nuclear-spin envionment}}$$



1. How is the signal processed: from the singlet and triplet products to biological signals?

2. Where is the magnetoreceptor?

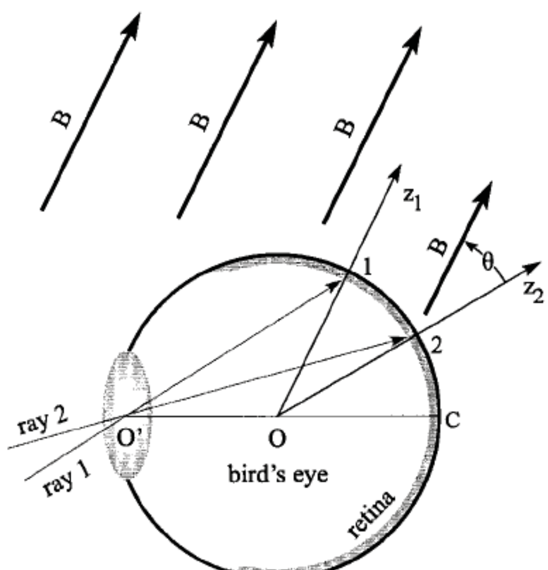
Avian Magnetoreception: Birds *see* magnetic fields

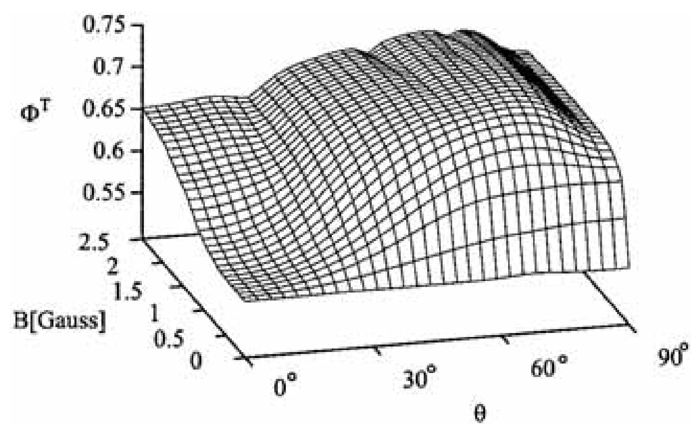


Biophysical Journal Volume 78 February 2000 707–718

A Model for Photoreceptor-Based Magnetoreception in Birds

Thorsten Ritz, Salih Adem, and Klaus Schulten
Theoretical Biophysics Group, Beckman Institute, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801 USA





Magnetic fields modulated vision pattern

Avian Magnetoreception: Birds *see* magnetic fields

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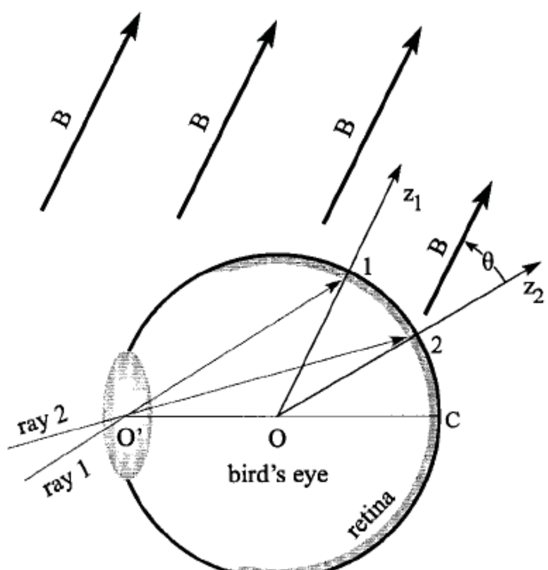

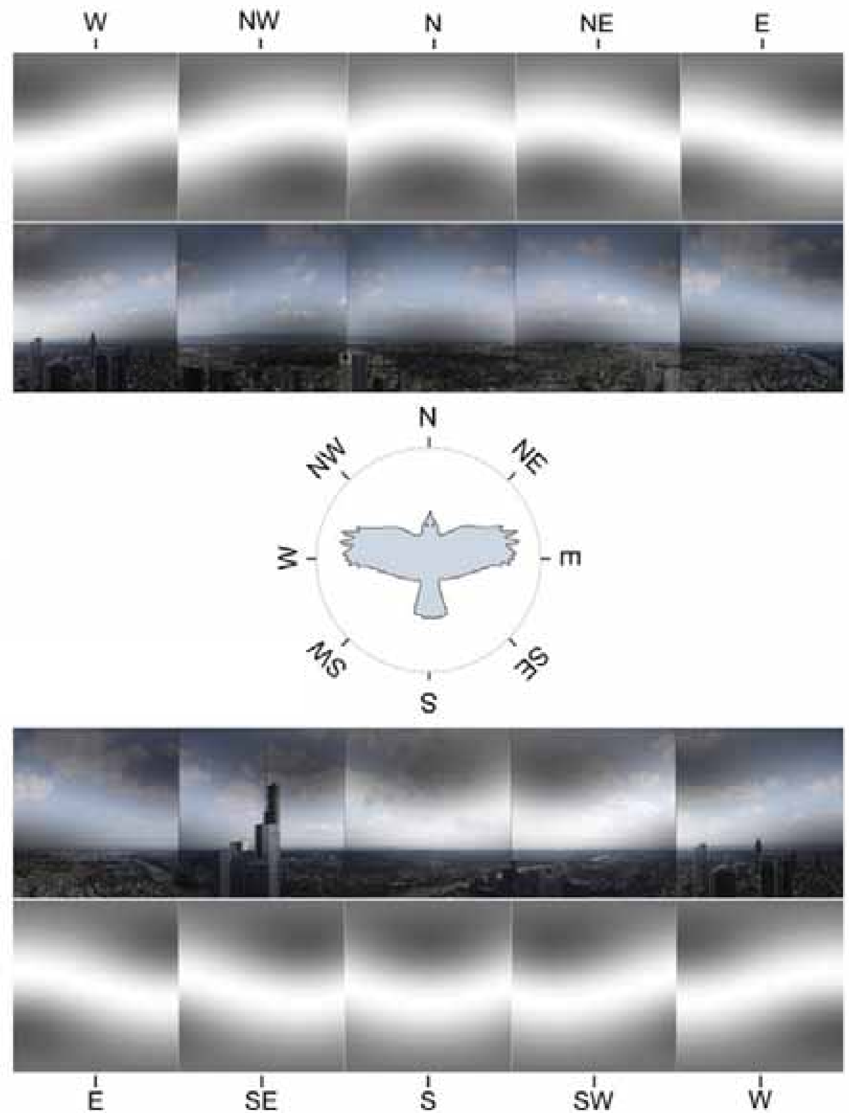

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Avian Magnetoreception: Radical pair mechanism

Biophysical Journal Volume 78 February 2000 707–718

A Model for Photoreceptor-Based Magnetoreception in Birds

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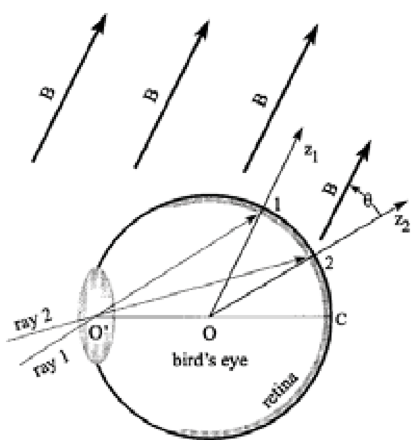
Dependence on the strength of geomagnetic field!

It is a strong argument against a magnetite-based compass!



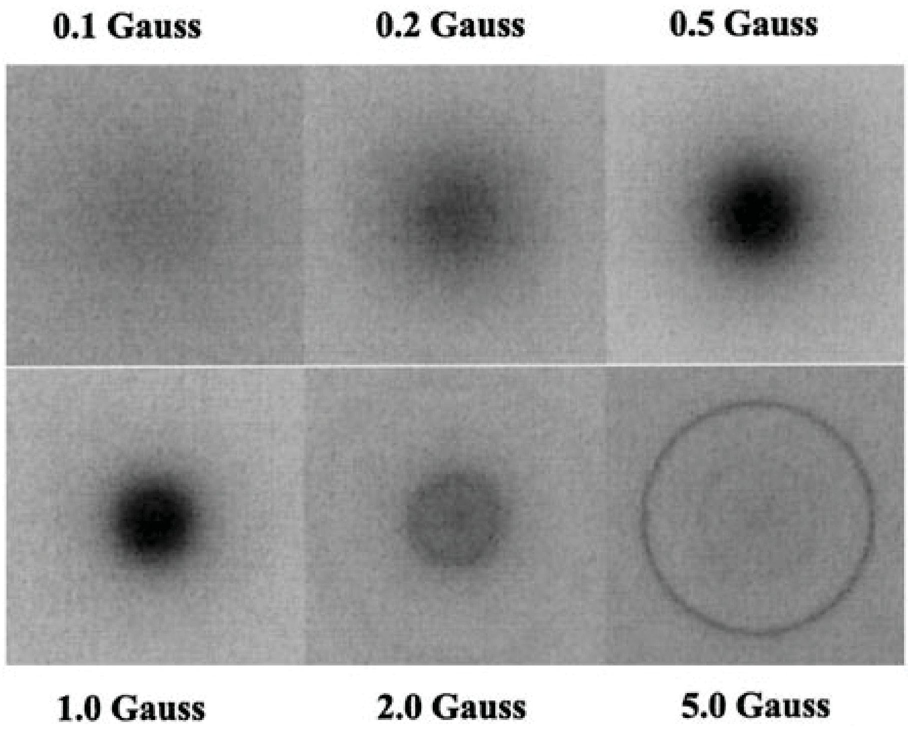
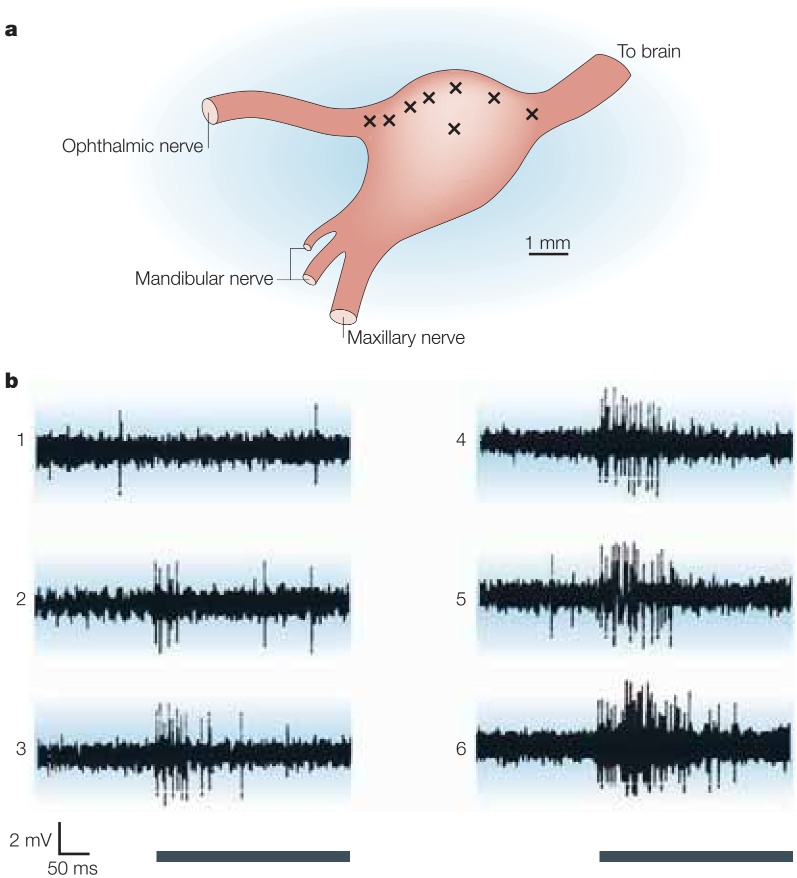


FIGURE 8 Visual modulation patterns through magnetic fields of 0.1, 0.2, 0.5, 1.0, 2.0, and 5.0 G for a bird looking parallel to the magnetic field lines. Changes in the field strength induce changes in the contrast of the modulation pattern, e.g., the central disk feature that is clearly visible for 0.5 and 1.0 G field strengths becomes less visible for lower and higher magnetic fields. In addition, qualitative changes can be observed, such as the occurrence of a new ring feature for higher (5 G) magnetic fields.

Avian Magnetoreception: Nerve signal tranduction

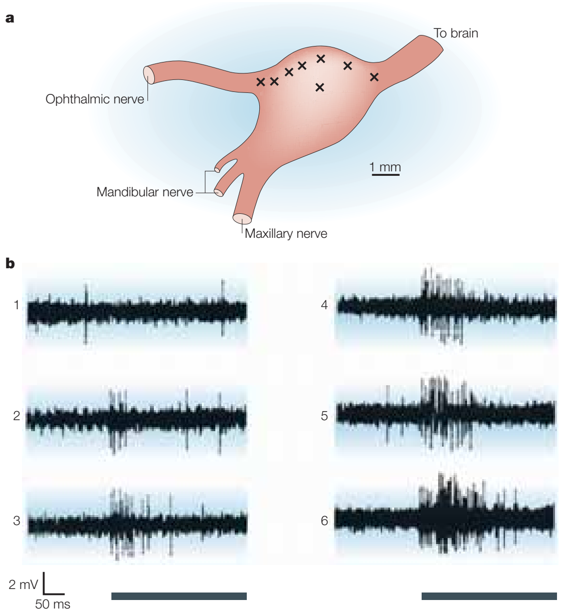


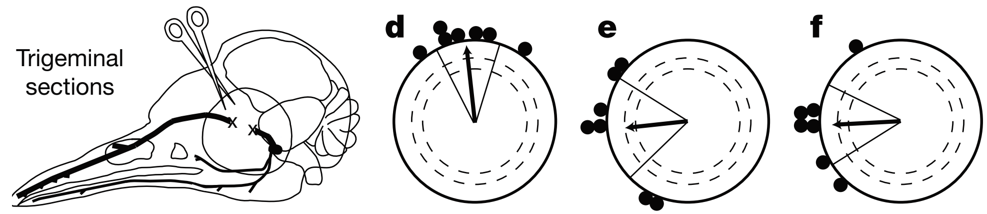
Branches of the trigeminal nerve innervate magnetoreceptors in birds

Recordings from one such ganglion cell during different changes in vertical magnetic field intensity (these changes also altered the inclination and total intensity of the field). (1) Spontaneous activity. (2) Response to 200 nanoTelsa (nT) change. (3) Response to 5,000 nT change. (4) Response to 15,000 nT change. (5) Response to 25,000 nT change. (6) Response to 100,000 nT change. The Earth's field is ~50,000 nT. Stimulus onset is indicated by the bar below each series.

Johnsen and Lohmann, Nature reviews (2005)

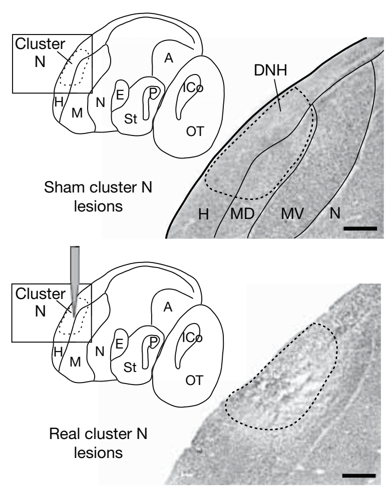
Avian Magnetoreception: Nerve signal tranduction

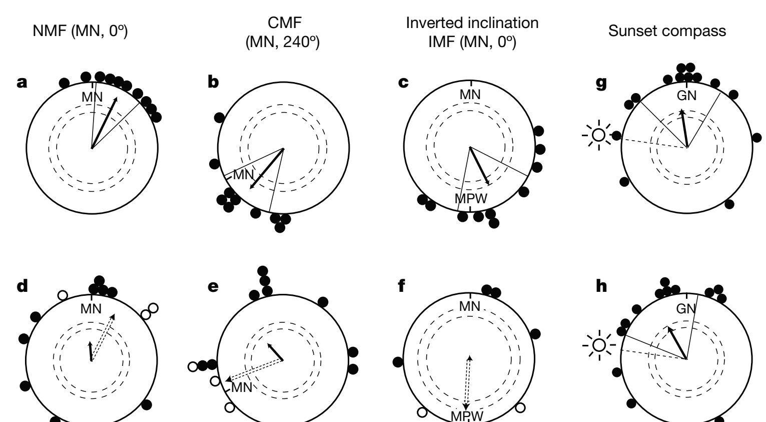




The iron-mineral-based receptors in the upper beak connected to the brain by the trigeminal nerve are neither necessary nor sufficient for magnetic compass orientation in European robins.

Cluster N is required for magnetic compass orientation in this species and indicate that it may be specifically involved in processing of magnetic compass information.





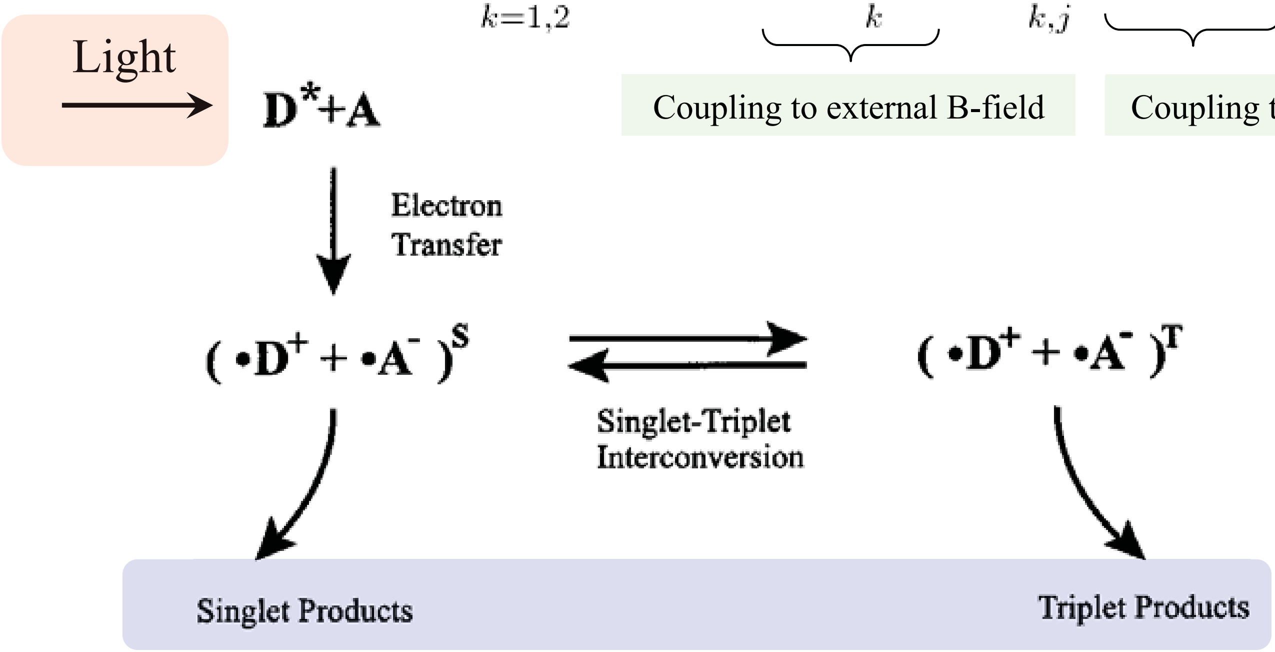
Henrik Mouritsen, Nature (2009)

Avian Magnetoreception: Where is the magnetoreceptor?

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

Coupling to external B-field

Coupling to local nuclear-spin envionment



$$\frac{d\rho_s}{dt} = -i[H_0, \rho_s] - \frac{k_S}{2} \sum_i (Q_S \rho_s + \rho_s Q_S) - \frac{k_T}{2} (Q_T \rho_s + \rho_s Q_T)$$

1. How is the signal processed: from the singlet and triplet products to biological signal

2. Where is the magnetoreceptor?

Avian Magnetoreception: Where is the magnetoreceptor?

1. Magnetic fields pass freely through biological tissue: magnetoreceptors need not to make contact with the external environment and might be located almost anywhere inside an animal's body.

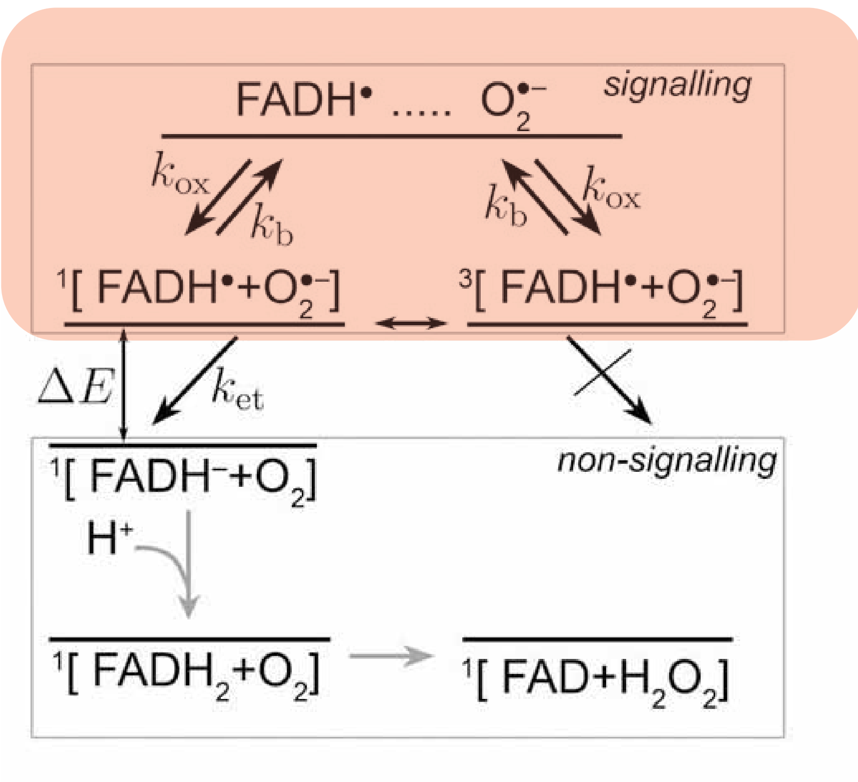
2. Magnetoreceptors might also be tiny and dispersed throughout a large volume of tissue

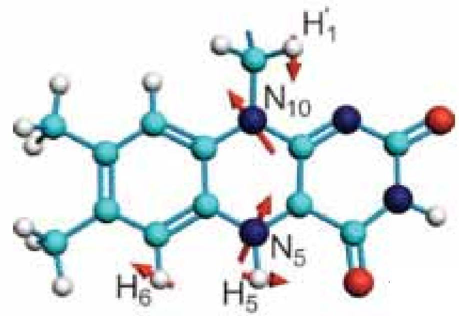
3. The transduction process might occur as a set of chemical reactions: no obvious organ or structure devoted to magnetorception necessarily exists.

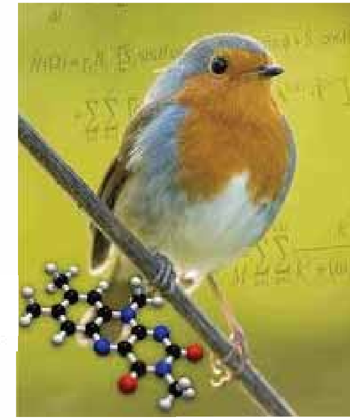
Kenneth J. Lohmann, Nature (2010)

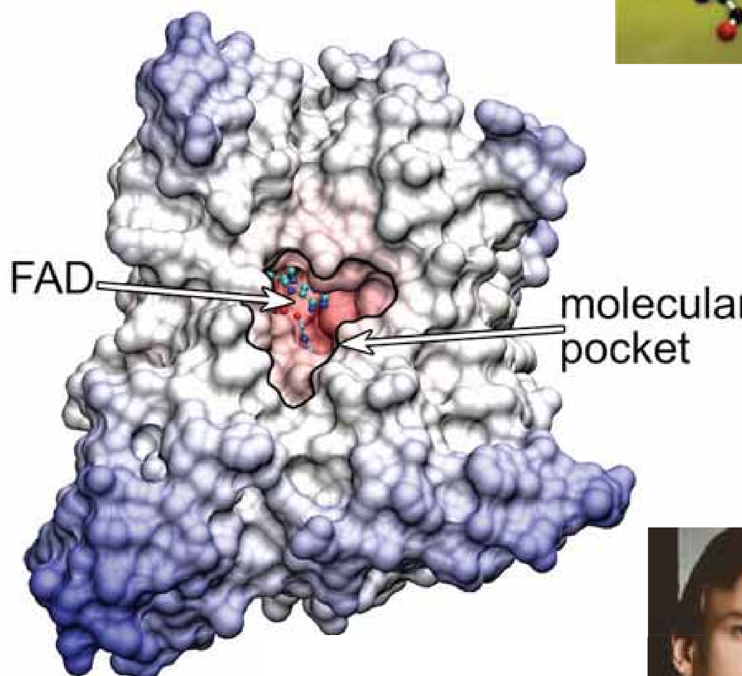
Avian Magnetoreception: Where is the magnetoreceptor?

Chromophore flavin-superoxide radical pair





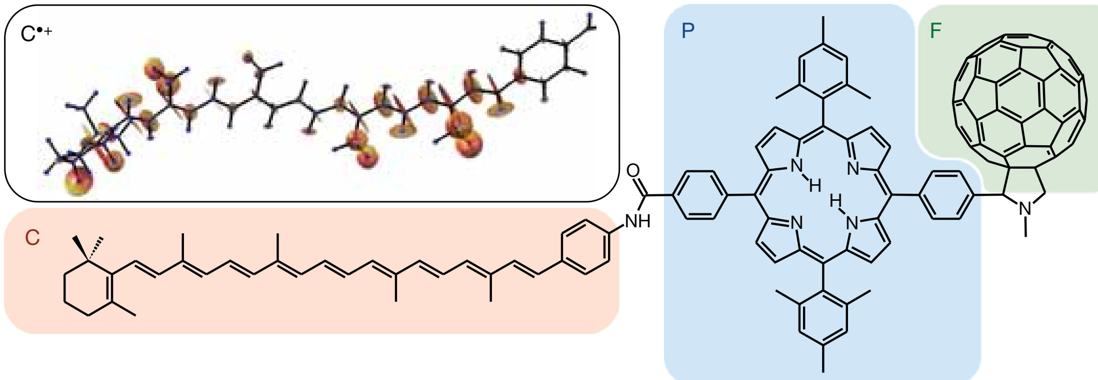


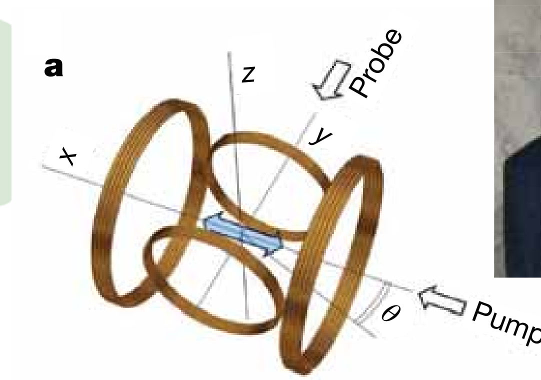


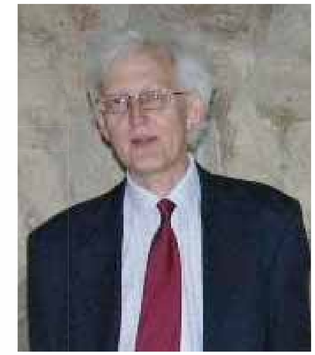
Klaus Schulten group

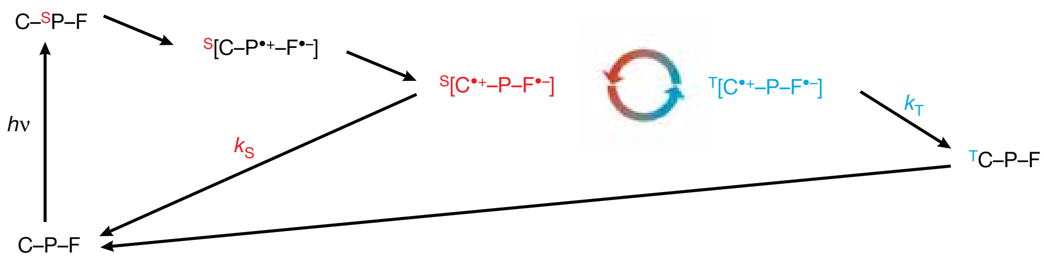
Ilia Solov'yov

Avian Magnetoreception: Probe-and-Reference model



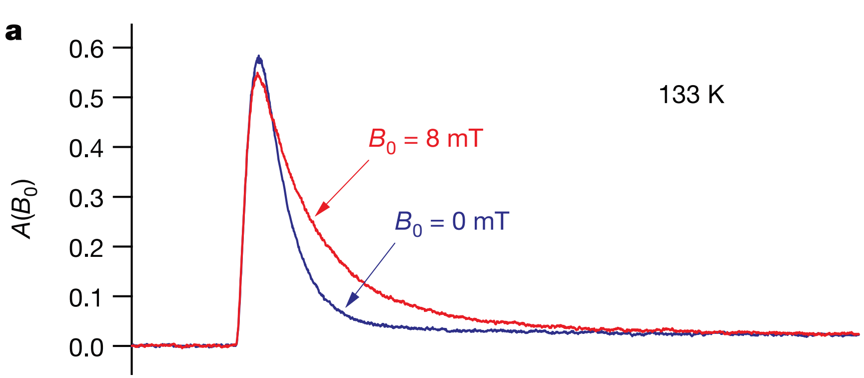


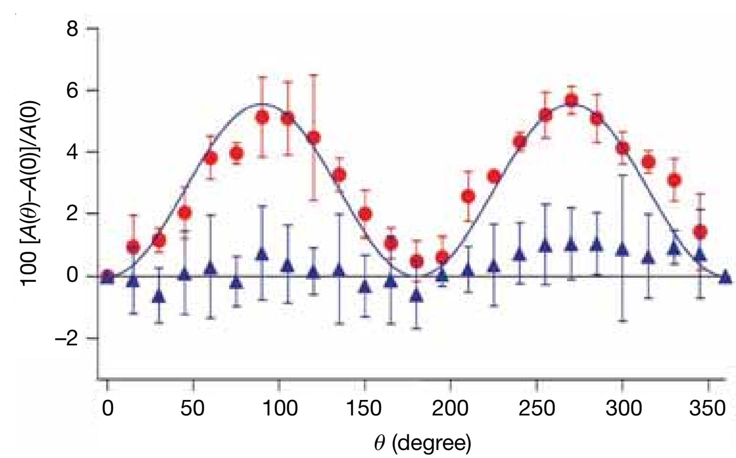




For the first time, the effect of Earth's magnetic field observed!

But at 193K!





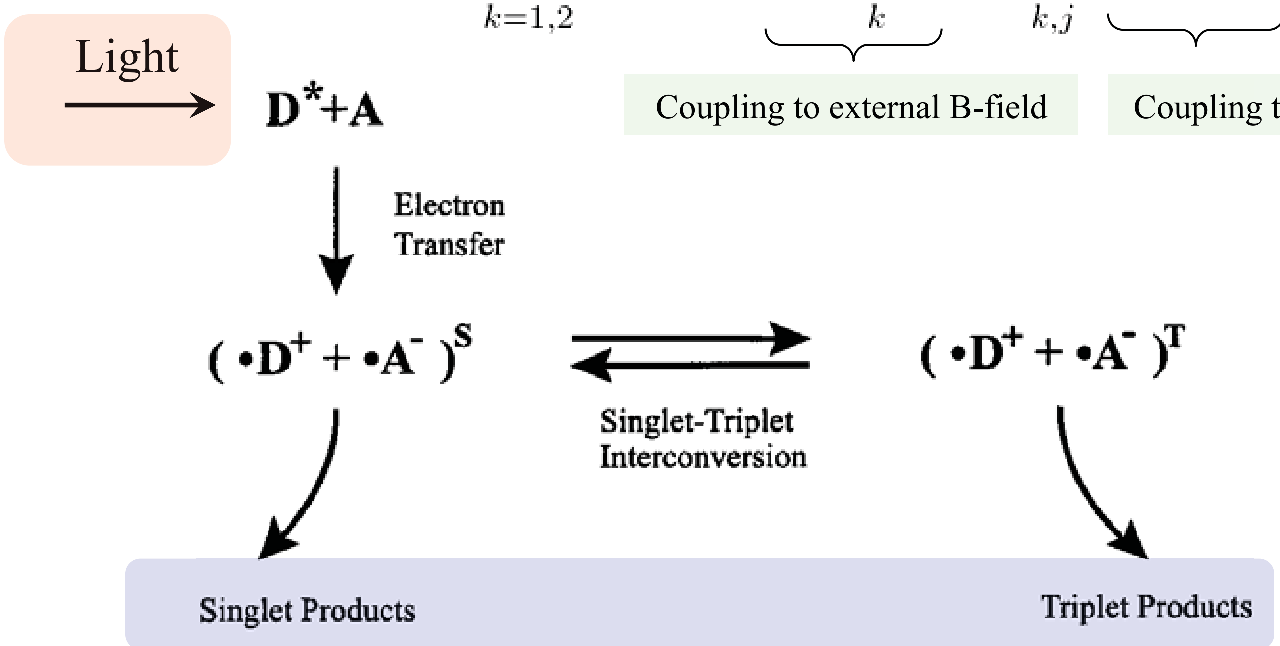
Peter Hore Nature (2008)

Avian Magnetoreception: Radical pair mechanism

$$H = \sum_{k=1,2} H_k = -\gamma_e \vec{B} \cdot \sum_k \vec{S}_k + \sum_{k,j} \vec{S}_k \cdot \hat{\lambda}_{k_j} \cdot \vec{I}_{k_j}$$

Coupling to external B-field

Coupling to local nuclear-spin envionment



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

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

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

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

$$\frac{d\rho_s}{dt} = -i[H_0, \rho_s] - \frac{k_S}{2} \sum_i (Q_S\rho_s + \rho_s Q_S) - \frac{k_T}{2} (Q_T\rho_s + \rho_s Q_T)$$

$$+ \mathcal{L}(\rho)$$

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

Jyrki's talk

Radical pair mechanism: Quantum Master Equations

Haberkorn Approach

Not trace preserving!?

$$\frac{d\rho_s}{dt} = -i[H_0, \rho_s] - \frac{k_S}{2}\sum_i (Q_S\rho_s + \rho_s Q_S) - \frac{k_T}{2}(Q_T\rho_s + \rho_s Q_T)$$

Radical pair mechanism: Quantum Master Equations

Measurement Approach I:

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

The Jones-Hore theory of radical-ion-pair reactions is not self-consistent

Iannis K. Kominis
Department of Physics, University of Crete, Heraklion 71103, Greece

Entropy Considerations in Spin-Selective Radical-Ion-Pair Reactions

Iannis K. Kominis
Department of Physics, University of Crete, Heraklion 71103, Greece

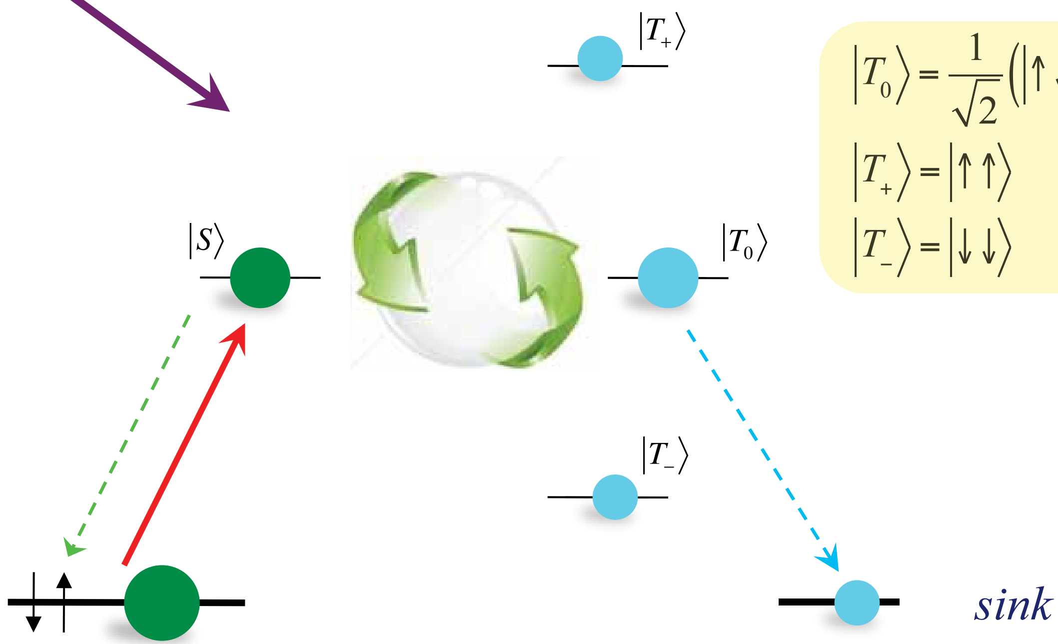
Radical-ion-pair reactions were recently shown to manifest a host of non-trivial quantum effects accounted for by quantum measurement theory. An alternative approach purporting to describe the fundamental quantum dynamics of spin-selective radical-ion pair reactions was introduced most recently, bringing to three the competing theories, including the one traditionally used in spin chemistry. We here consider entropy as a fundamental concept enabling a comparison of the predictions of these theories against what is physically acceptable on quite general grounds.

Radical pair mechanism: Quantum Master Equations

$h\nu$ → $D^+ - A^-$ $\uparrow \cdots \downarrow$ → Charge recombination

Trace non-preserving?

spin coherent dynamics



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

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

- Haberkorn Approach

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

$$\Phi_S = k\int_0^\infty \mathrm{Tr}\left[Q_S\rho(t)\right] dt$$

$$k_S = k_T$$

U. E. Steiner and T. Ulrich, Chem. Rev. 89, 51-147 (1989)

Radical pair mechanism: Quantum Master Equations

Measurement Approach II:

$$\frac{d\rho_s}{dt} = -i[H_0, \rho_s] - (k_S + k_T)\rho_s + k_S Q_T \rho_s Q_T + k_T Q_S \rho_s Q_S$$

Spin-selective reactions of radical pairs act as quantum measurements

J.A. Jones[a,b], P.J. Hore[c,*]

[a] Centre for Quantum Computation, Clarendon Laboratory, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom
[b] Centre for Advanced ESR, University of Oxford, South Parks Road, Oxford OX1 3QR, United Kingdom
[c] Department of Chemistry, University of Oxford, Physical and Theoretical Chemistry Laboratory, South Parks Road, Oxford OX1 3QZ, UK

A R T I C L E I N F O

Article history:
Received 21 November 2009
In final form 26 January 2010
Available online xxxx

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Since the 1970s, spin-selective reactions of radical pairs have been modelled theoretically by adding phenomenological rate equations to the quantum mechanical equation of motion of the radical pair spin density matrix. Here, using a quantum measurement approach, we derive an alternative set of rate expressions which predict a faster decay of coherent superpositions of the singlet and triplet radical pair states. The difference between the two results, however, is not dramatic and would probably be difficult to distinguish experimentally from decoherence arising from other sources.

Radical pair mechanism: Quantum Master Equations

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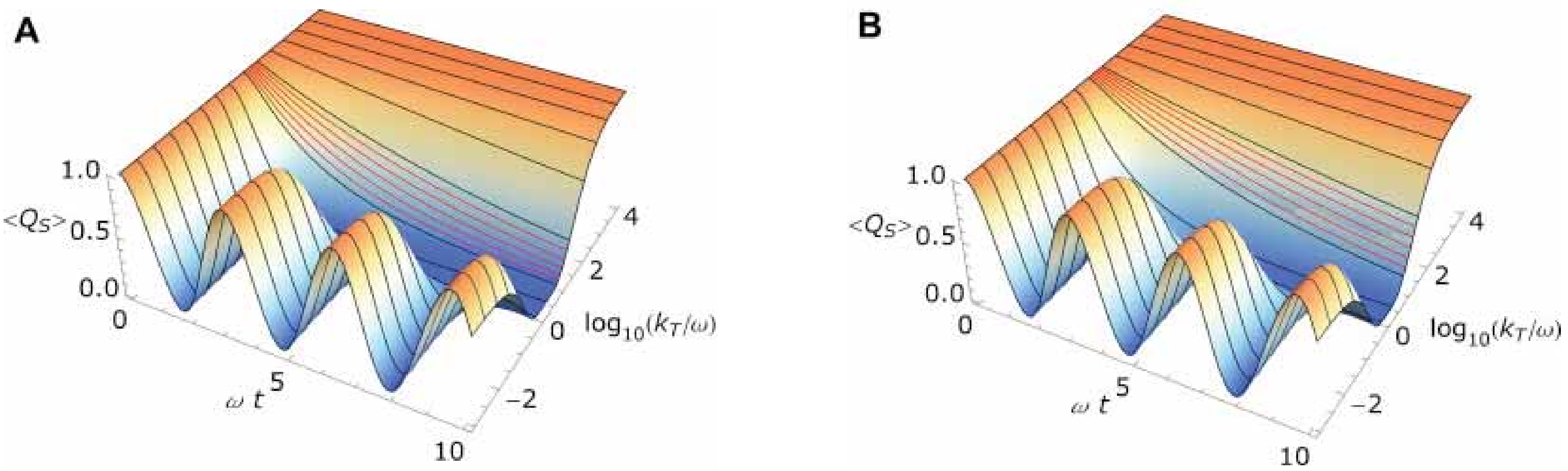


Radical pair mechanism: Quantum Master Equations

Haberkorn Approach

$$\frac{d\rho_s}{dt} = -i[H_0, \rho_s] - \frac{k_S}{2}\sum_i (Q_S\rho_s + \rho_s Q_S) - \frac{k_T}{2}(Q_T\rho_s + \rho_s Q_T)$$

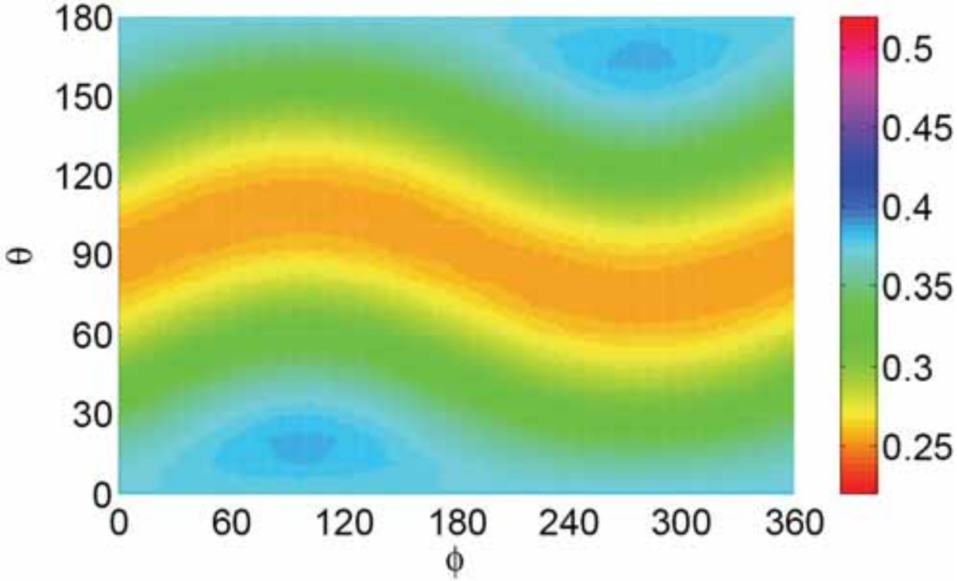
Quantum Measurement Master Equation:

$$\frac{d\rho_s}{dt} = -i[H_0, \rho_s] - (k_S + k_T)\rho_s + k_S Q_T \rho_s Q_T + k_T Q_S \rho_s Q_S$$

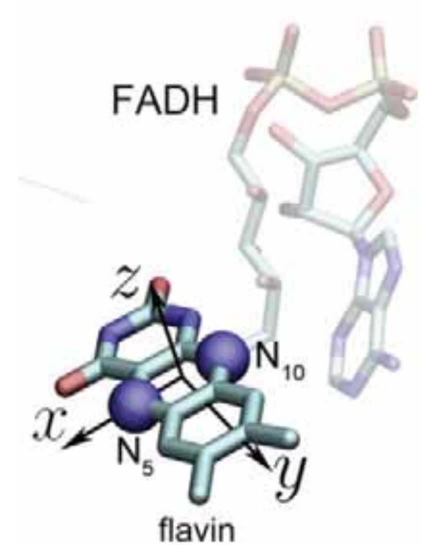
Nucleus	a_{iso}	λ_i	Principal hyperfine axes		
N	0.393	-0.498	0.4380	0.8655	-0.2432
		-0.492	0.8981	-0.4097	0.1595
		0.989	-0.0384	0.2883	0.9568
N	0.212	-0.242	0.9703	-0.2207	0.0992
		-0.234	0.2383	0.9426	-0.2340
		0.476	-0.0419	0.2506	0.9672
H	0.390	-0.062	-0.1902	0.3965	0.8981
		-0.033	0.9156	0.4017	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

$$\Psi_S = k_S \int_0^\infty Tr[Q_S \rho_s(t)]dt$$

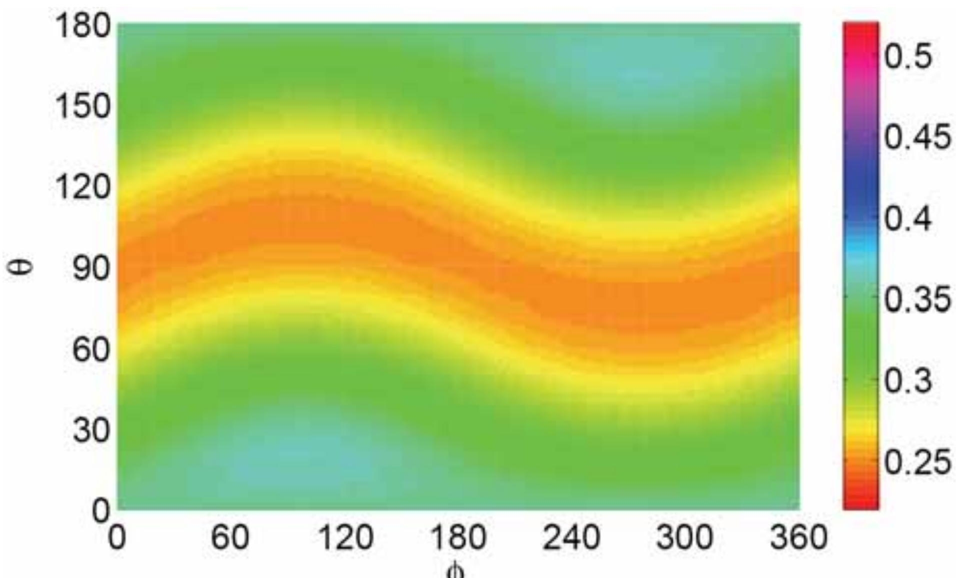
Radical pair mechanism: Quantum Master Equations



Haberkorn Approach



Quantum Measurement ME



JMC, Phys Rev Lett (2011)

Radical pair mechanism: Quantum Master Equations

Spin-selective reactions of radical pairs act as quantum measurements

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Haberkorn Approach

$$\frac{d\rho_s}{dt} = -i[H_0, \rho_s] - \frac{k_S}{2} \sum_i (Q_S\rho_s + \rho_s Q_S) - \frac{k_T}{2} (Q_T\rho_s + \rho_s Q_T)$$

Radical pair mechanism: Quantum Master Equations

Haberkorn Approach

$$\frac{d\rho_s}{dt} = -i[H_0, \rho_s] - \frac{k_S}{2}\sum_i (Q_S\rho_s + \rho_s Q_S) - \frac{k_T}{2}(Q_T\rho_s + \rho_s Q_T)$$

J. Phys. Chem. A **2010,** *114,* 9447–9455 **9447**

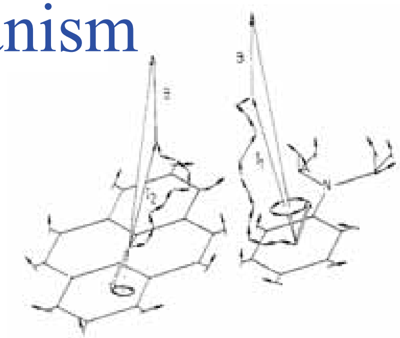
Consistent Treatment of Spin-Selective Recombination of a Radical Pair Confirms the Haberkorn Approach

Konstantin L. Ivanov,*,† Marina V. Petrova,†,‡ Nikita N. Lukzen,† and Kiminori Maeda*,§

International Tomography Center SB RAS, Novosibirsk, 630090, Russia, Novosibirsk State University, Novosibirsk, 630090, Russia, and Centre for Advanced Electron Spin Resonance, University of Oxford, Oxford, OX1 3QR, U.K.

In the present work, we have shown that consistent derivation of the kinetic equations describing the electron spin-selective recombination of radical pairs confirms the conventional Haberkorn approach. The derivation has been based on considering the interaction of the reactive system (radical pair and product state) with the thermal bath. The consistency of this approach has also been substantiated by numerical simulations performed for the purely quantum mechanical model of the recombining radical pair. Finally, we have shown that the quantum Zeno effect on radical pair recombination is not an exclusive feature of the approach recently proposed by Kominis, as it should be present at any rate of the singlet−triplet dephasing in the radical pair, which always accompanies the recombination process.

Avian Magnetoreception: Radical pair mechanism



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Coupling to external B-field

Coupling to local nuclear-spin envionment

Light

$D^* + A$

Electron Transfer

$(\bullet D^+ + \bullet A^-)^S \rightleftharpoons (\bullet D^+ + \bullet A^-)^T$

Singlet-Triplet Interconversion

Singlet Products

Triplet Products

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

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

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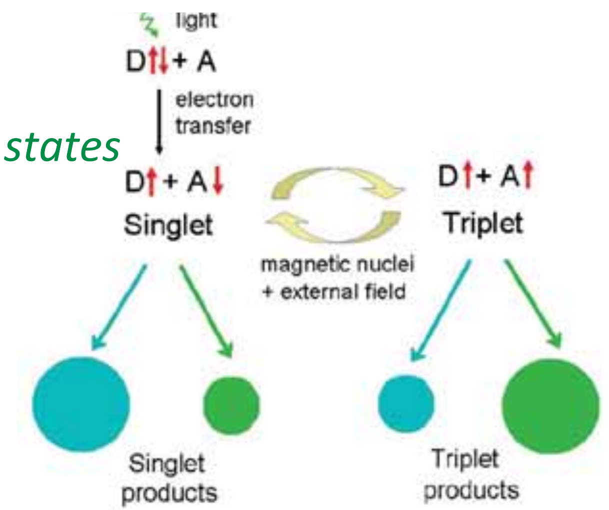
Coherent dynamics and design principles for a chemical compass

- 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*

Second talk this afternoon

Thank you very much for your attention!